ESC201T : Introduction to Electronics

Lecture 29: Operational Amplifier

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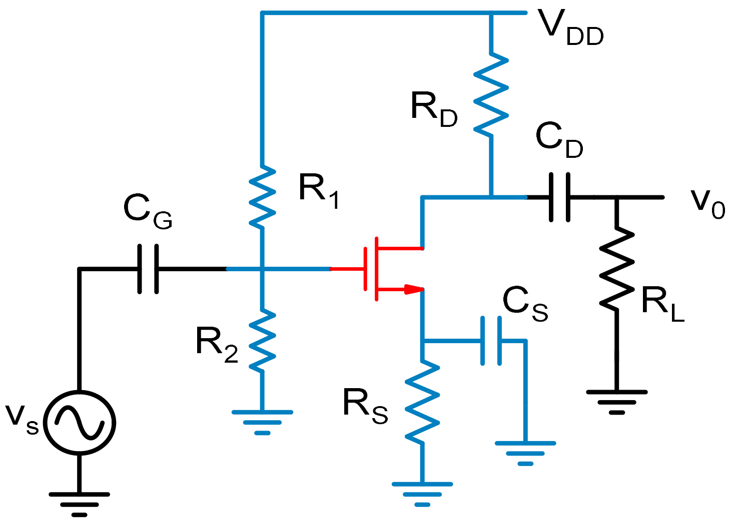
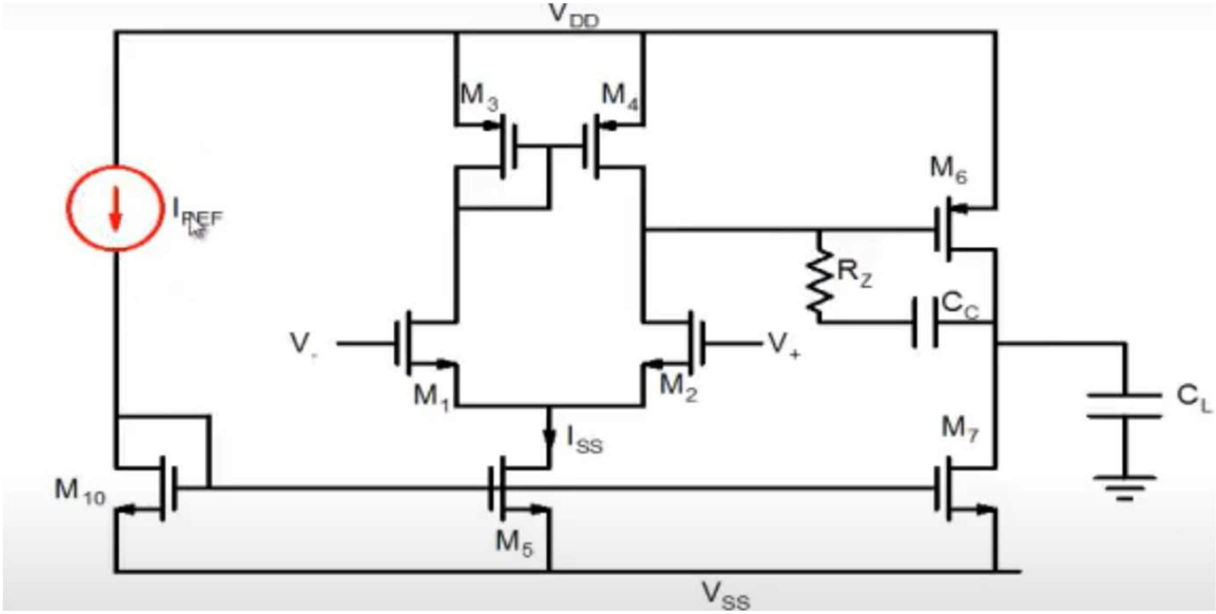
Amplifier Design requires specialized knowledge





It is not possible for every user to design his/her own amplifier !

Why can't we have experts design and implement amplifiers and make it available to everybody else !

Although this is done, it does not satisfy all the users due to diverse requirements

Custom

Design

Semi-Custom

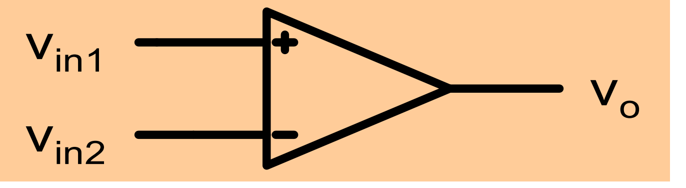
Standard

Semi-custom: partially competed design which is customized by the user

Opamp is a good illustration of the advantages of semi-custom approach

Difference Amplifier

-An amplifier that is sensitive to difference in input voltages and insensitive to what is common.



$$v_{id} = v_{in1} - v_{in2}$$

$$v_{ic} = \frac{v_{in1} + v_{in2}}{2}$$

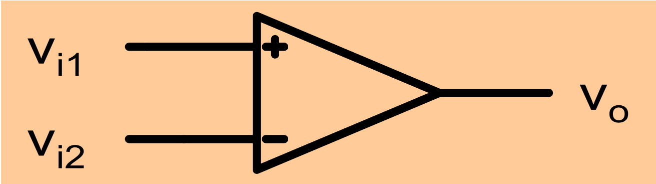
$$v_o = A_d v_{id} + A_{cm} v_{ic}$$

A_d : Differential mode gain

A_{cm} : Common mode gain

$$A_d \gg A_{cm}$$

Common Mode Rejection Ratio: $CMRR = \frac{A_d}{A_{cm}}$



$$A_d = 100; \quad A_{cm} = 0.01$$

$$v_{i1} = 1V + 5mV \times Sin(\omega t)\ ;\ v_{i2} = 1V - 5mV \times Sin(\omega t)$$

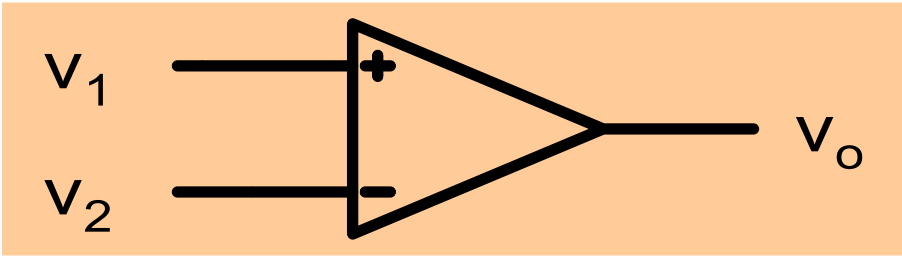
$$v_{id} = v_{in1} - v_{in2} = 10mV \times Sin(\omega t)$$

$$v_{ic} = \frac{v_{in1} + v_{in2}}{2} = 1V$$

$$v_o = A_d v_{id} + A_{cm} v_{ic}$$
$$= 1V \times Sin(\omega t) + 10mV$$

Whatever is common is rejected and whatever is different is amplified !

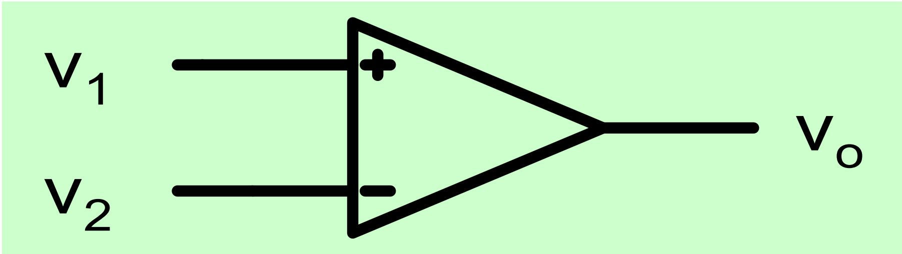
Operational Amplifier



A special kind of difference amplifier

1. Very High Differential-mode voltage gain
2. Very High Common mode Rejection ratio
3. Very High Input Resistance
4. Very Low output Resistance
5. ….

Ideal Operational Amplifier



1. Infinite Differential-mode voltage gain
2. Infinite Common mode Rejection ratio
3. Infinite Input Resistance
4. Zero output Resistance
5. ….

Example: LM 741

LM741
Operational Amplifier

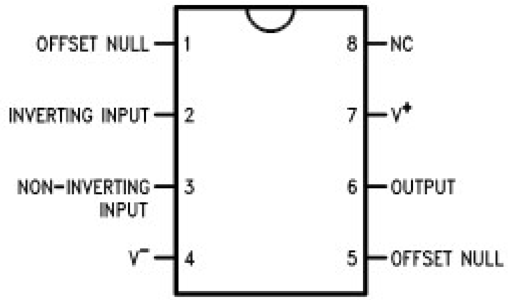
General Description

The LM741 series are general purpose operational amplifiers which feature improved performance over industry standards like the LM709. They are direct, plug-in replacements for the 709C, LM201, MC1439 and 748 in most applications.

The amplifiers offer many features which make their application nearly foolproof: overload protection on the input and output, no latch-up when the common mode range is exceeded, as well as freedom from oscillations.

The LM741C is identical to the LM741/LM741A except that the LM741C has their performance guaranteed over a 0°C to +70°C temperature range, instead of −55°C to +125°C.

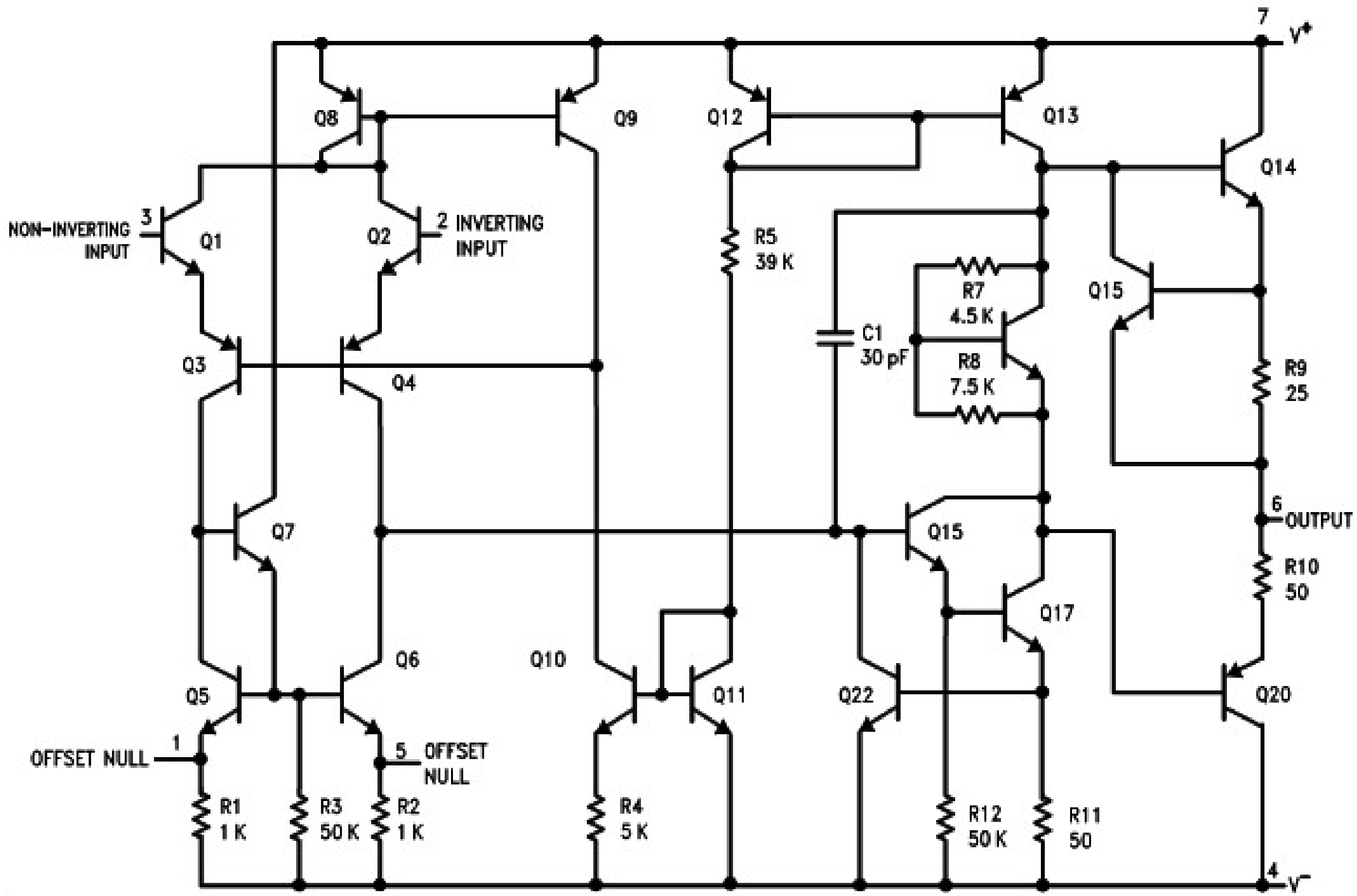
Dual-In-Line or S.O. Package



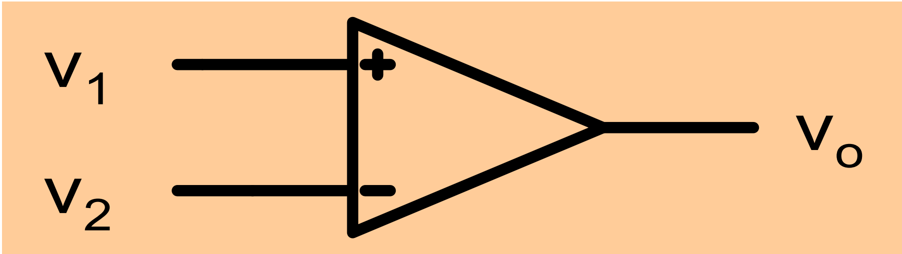
Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Resistance	T_A = 25°C, V_S = ±20V	1.0	6.0		0.3	2.0		0.3	2.0		MΩ
	$T_{AMIN} \le T_A \le T_{AMAX}$, V_S = ±20V	0.5									MΩ
Large Signal Voltage Gain	T_A = 25°C, $R_L \ge$ 2 kΩ										
	V_S = ±20V, V_O = ±15V	50									V/mV
	V_S = ±15V, V_O = ±10V				50	200		20	200		V/mV
Common-Mode	$T_{AMIN} \le T_A \le T_{AMAX}$										
Rejection Ratio	$R_S \le$ 10 kΩ, V_{CM} = ±12V				70	90		70	90		dB
	$R_S \le$ 50Ω, V_{CM} = ±12V	80	95								dB

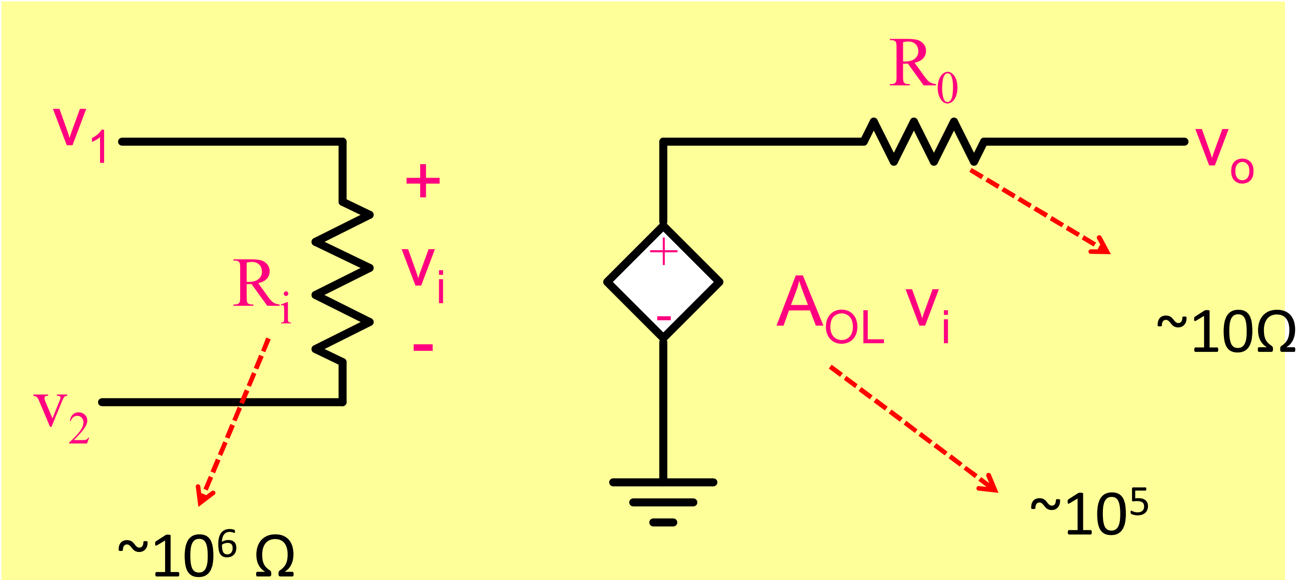
Inside the opamp, there is a complicated circuit containing several transistors and resistors.

Schematic Diagram

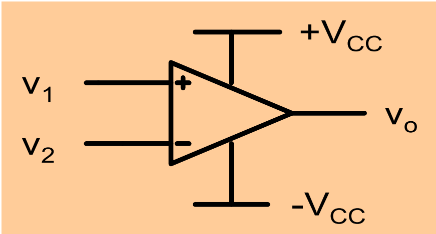


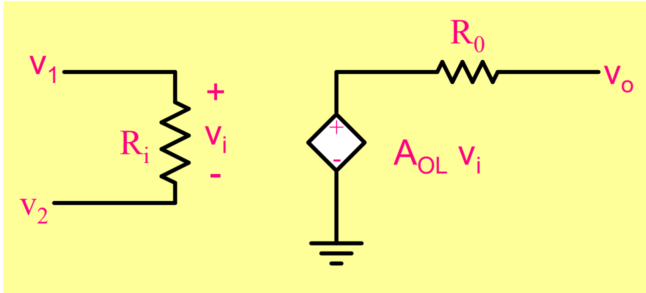
Simple equivalent circuit model of an opamp



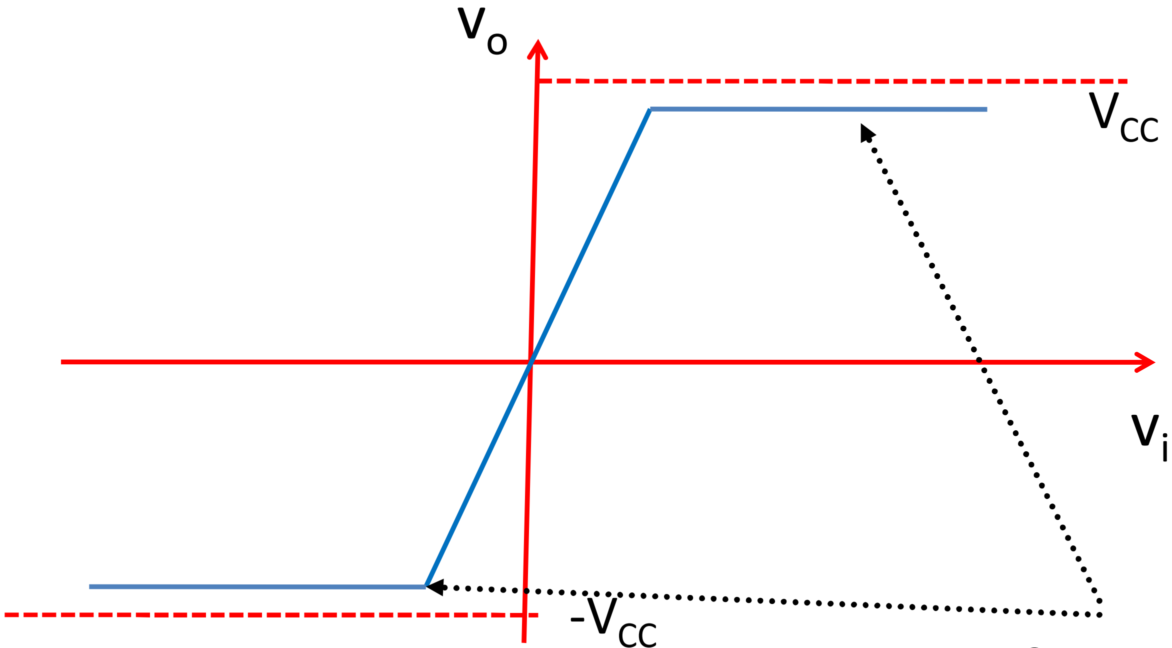


This assumes very high CMRR

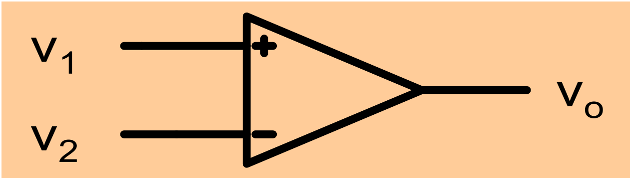


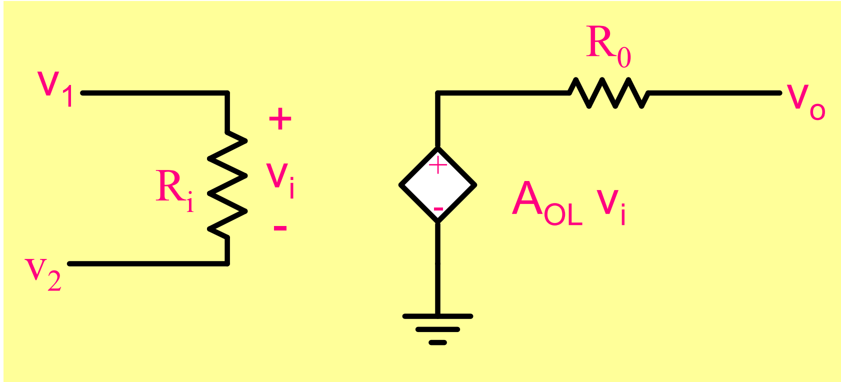


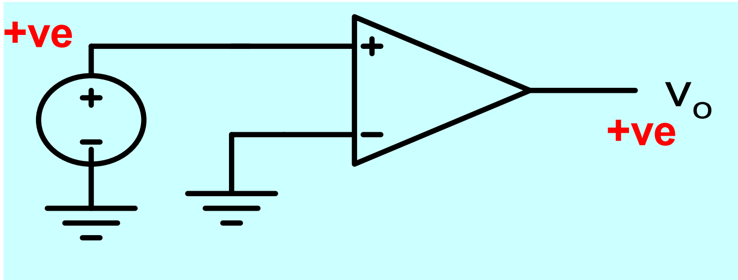
$$v_o = A_{ol} \times v_i$$

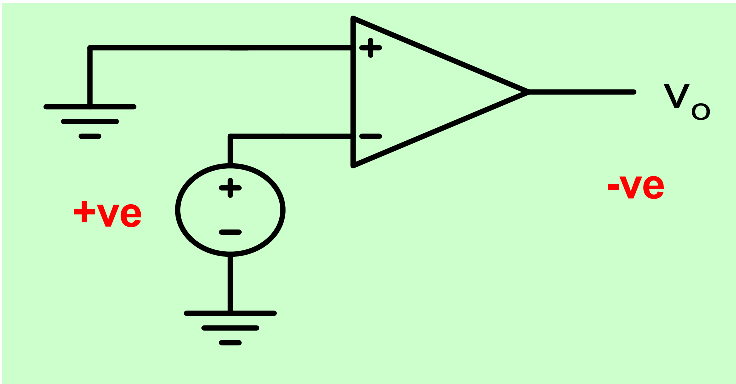


Opamp is said to be saturated

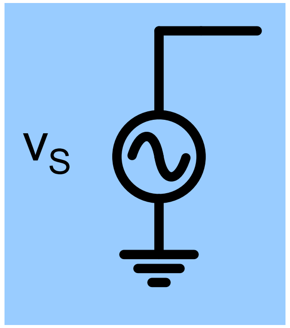

v1
v2
+
-
vo


v1
v2
Ri
+
vi
-
R0
vo
AOL vi

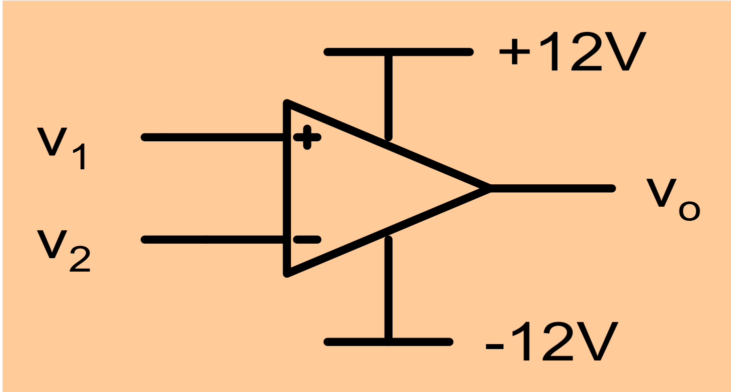

+ve
+
-
vo
+ve

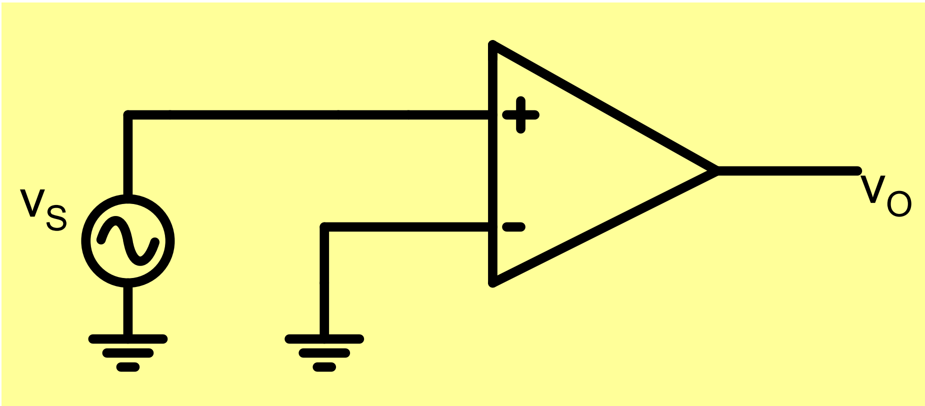

+
-
vo
+ve
-ve

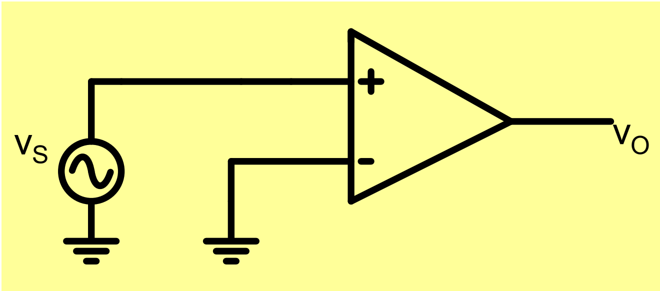
How do we amplify this signal?

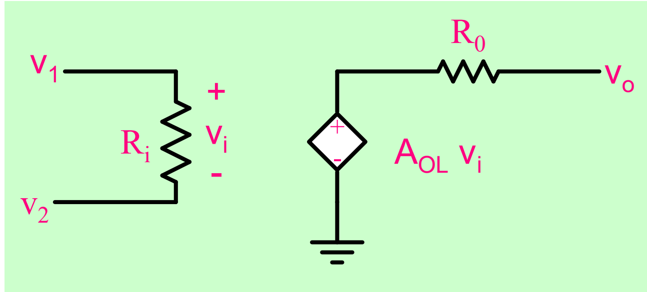


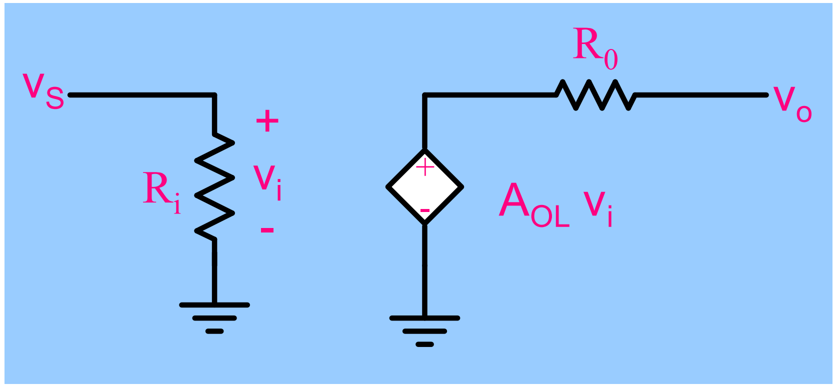
$$v_s = 1mV\ Sin(\omega t)$$







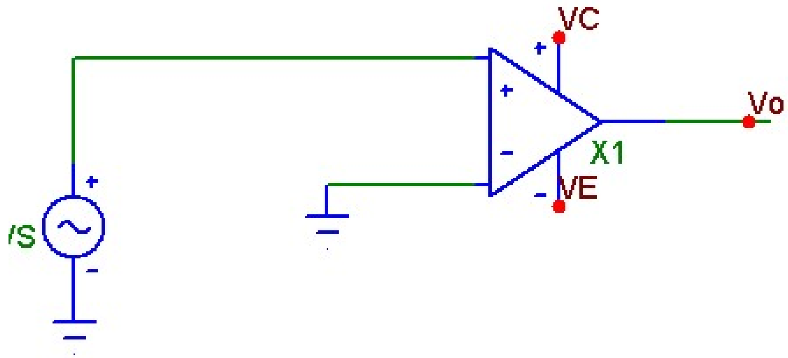


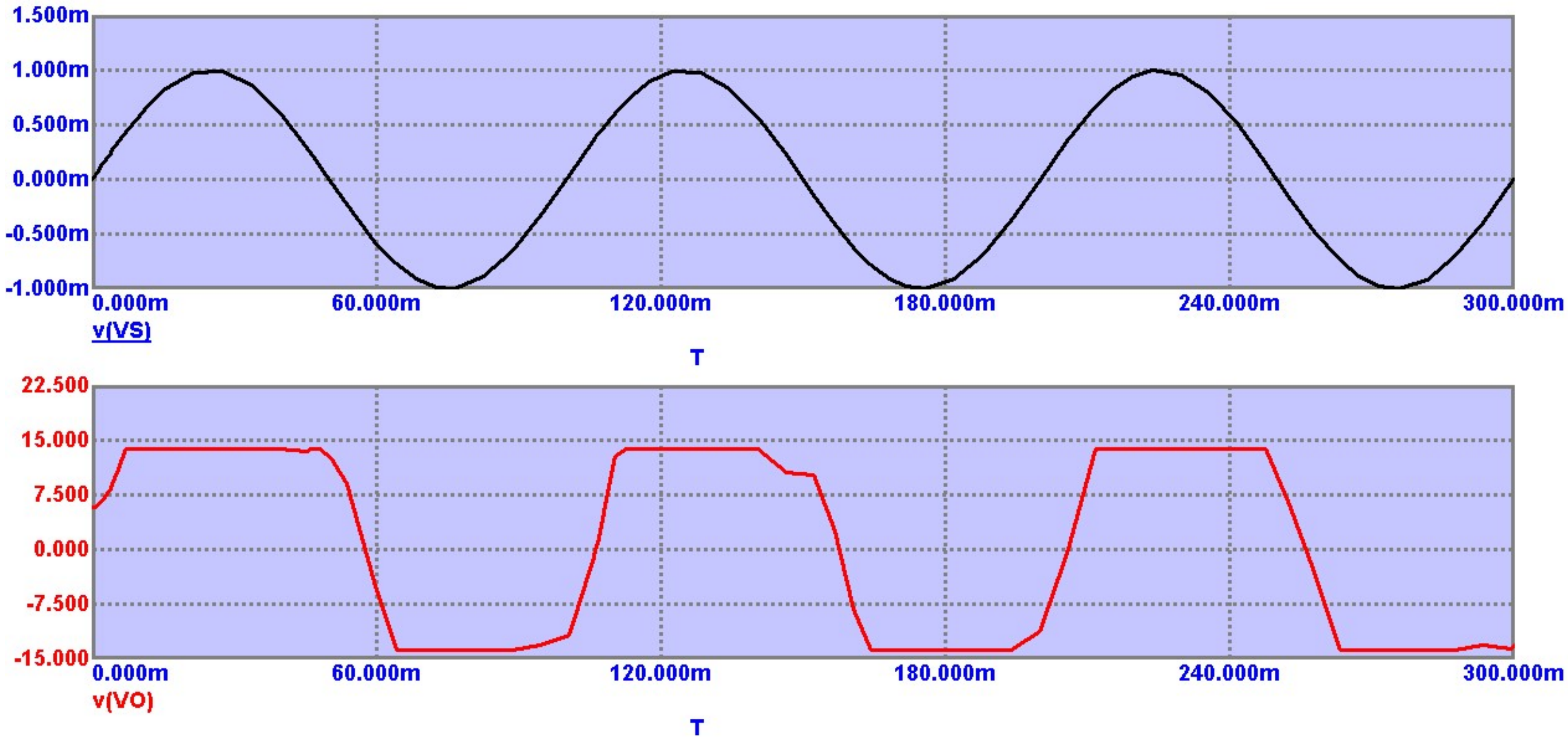


$$v_o = A_{ol} \times v_S = 10^2 \, Sin(\omega t)$$

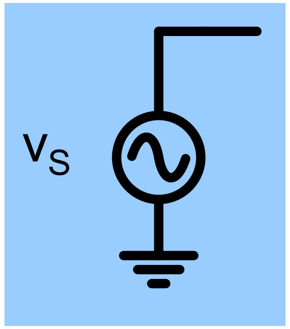
But opamp voltage is limited to $\pm 12V$

Simulation Results

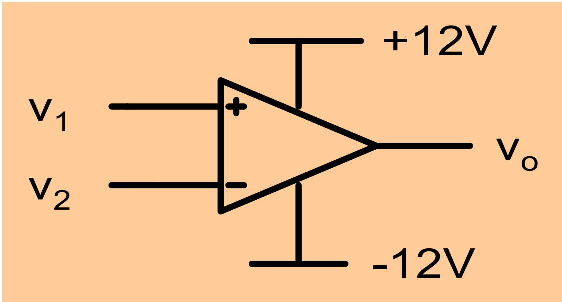


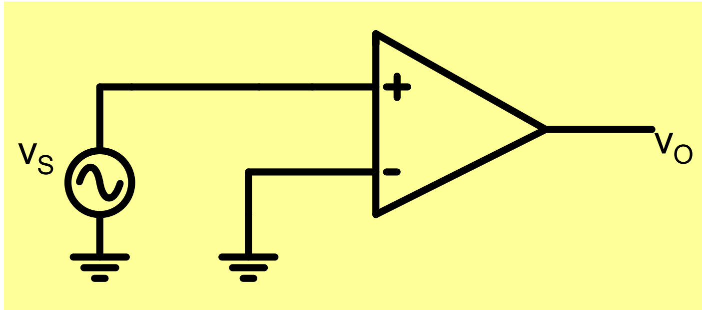


How do we amplify this signal then ?



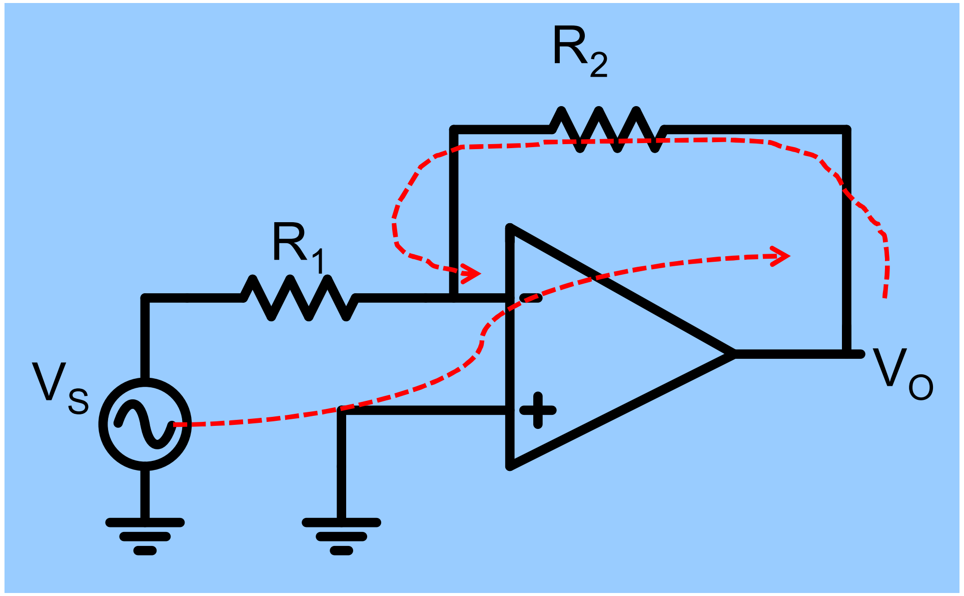
$v_S = 1mV\ Sin(\omega t)$





1. Attenuate the signal to 0.1mV and then amplify ?
2. …….

A Better Solution

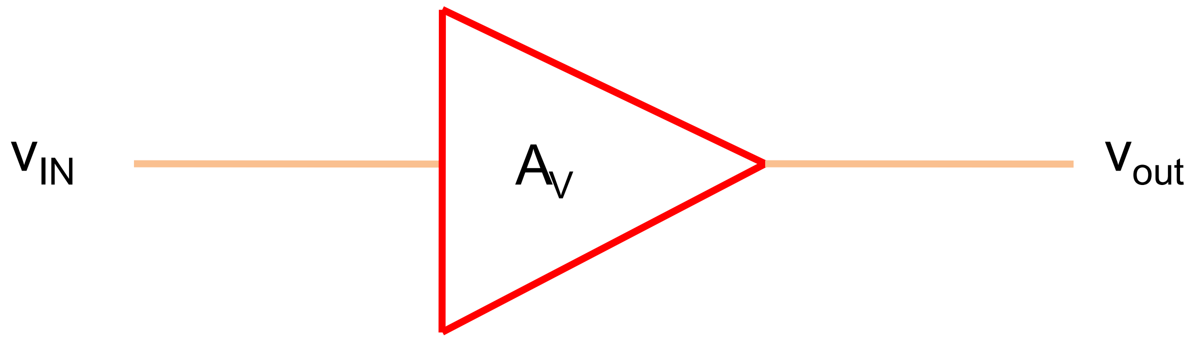


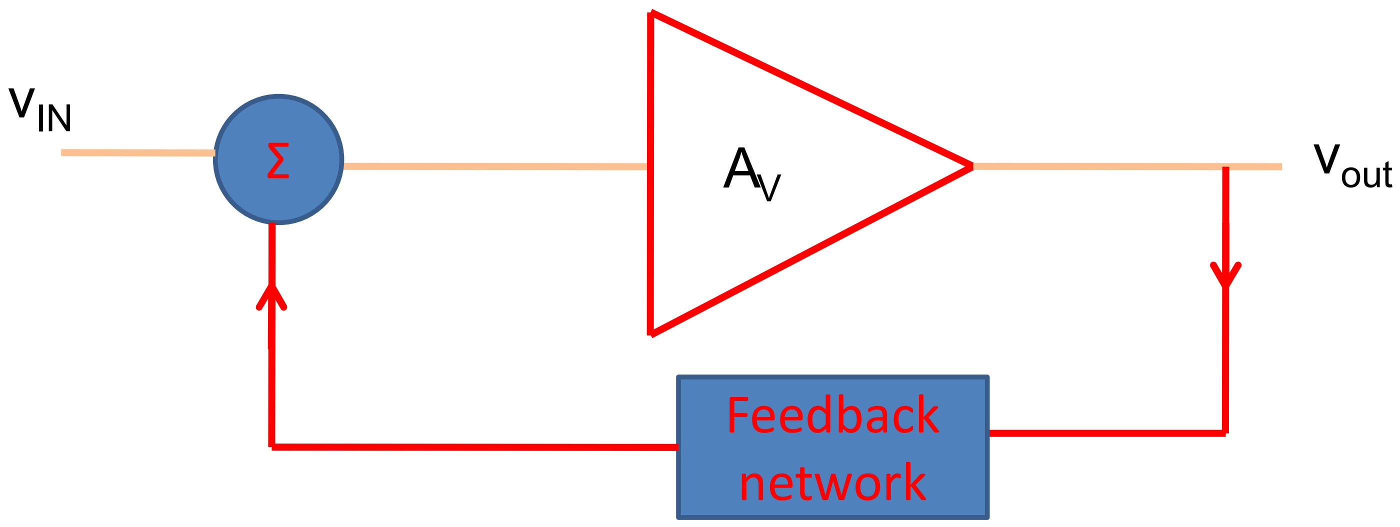
$$\frac{v_o}{v_S} = -\frac{R_2}{R_1}$$

Amplifier has feedback

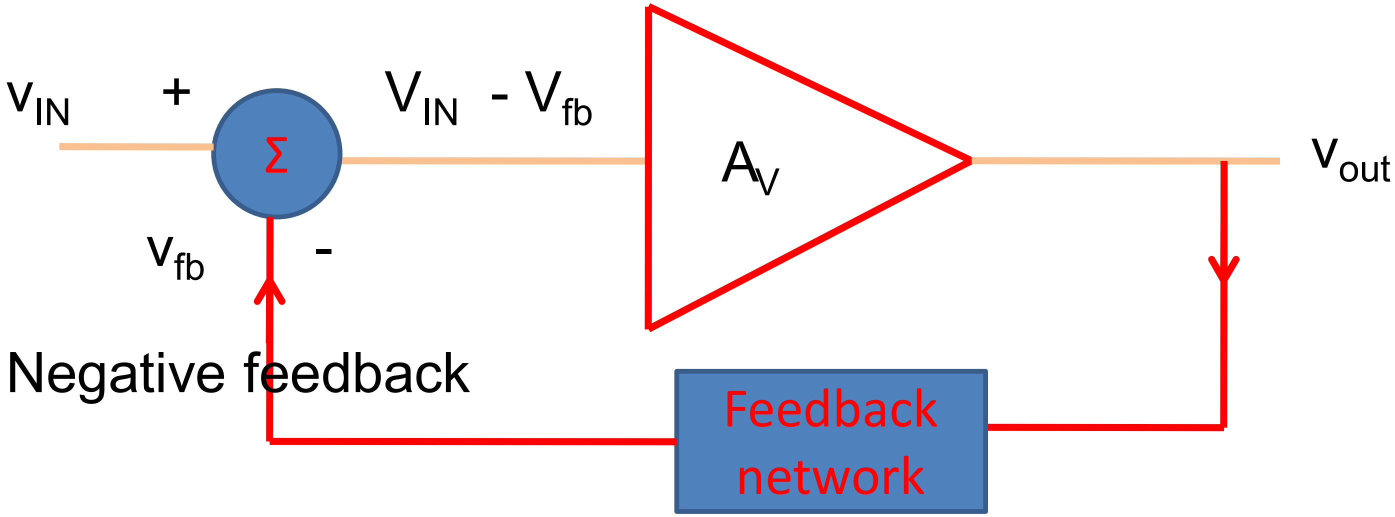
If the feedback signal helps the input voltage we have positive feedback, otherwise negative.

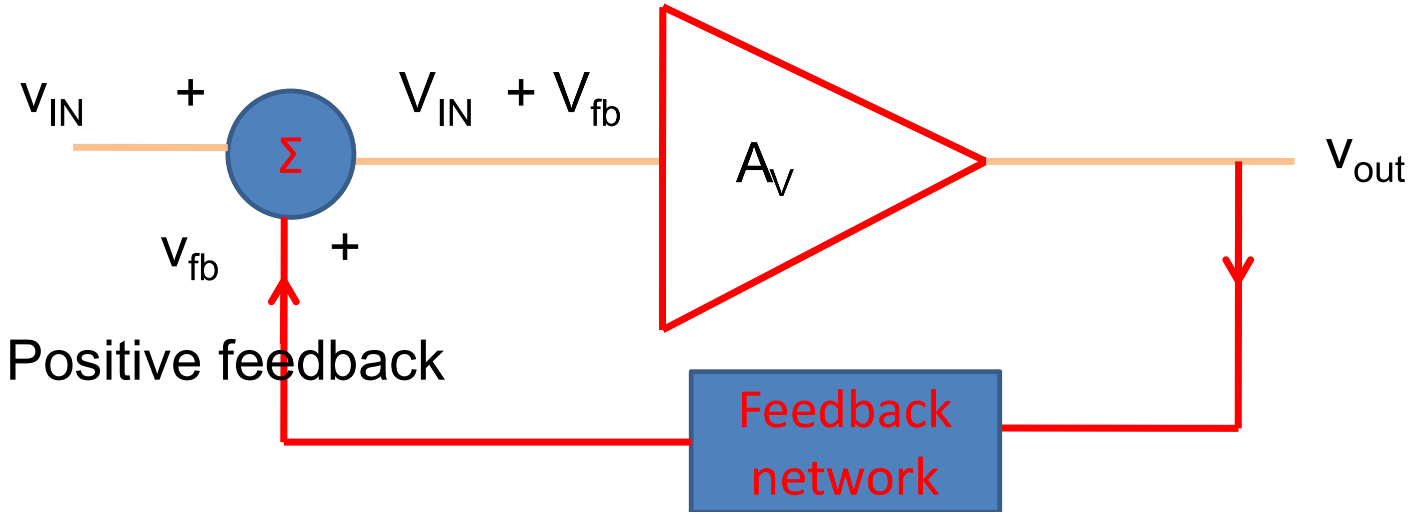
Feedback



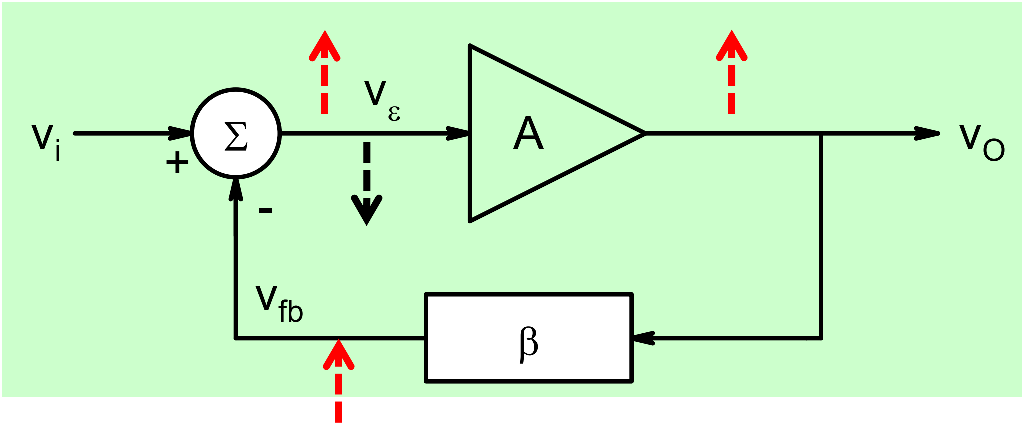


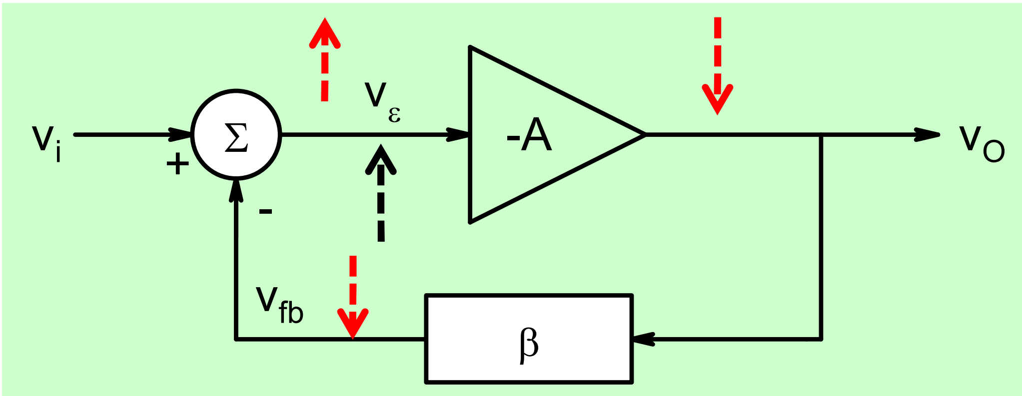
Negative and Positive feedback





Negative and positive feedback





Opamp circuits classification

Negative feedback

Closed loop
Or feedback

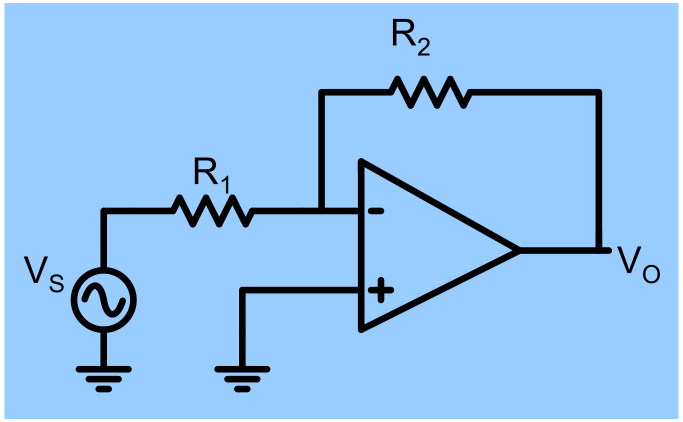
Opamp circuits

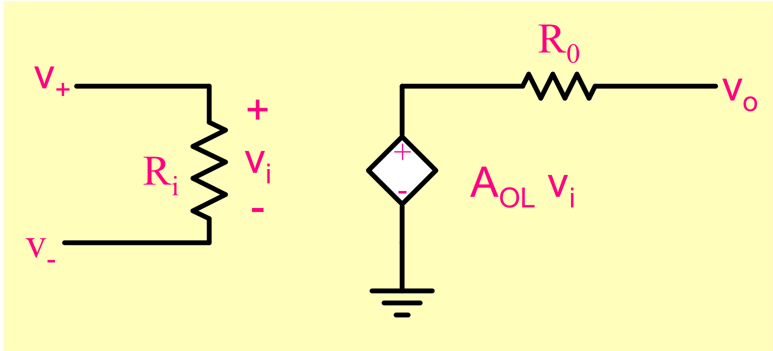
Positive feedback

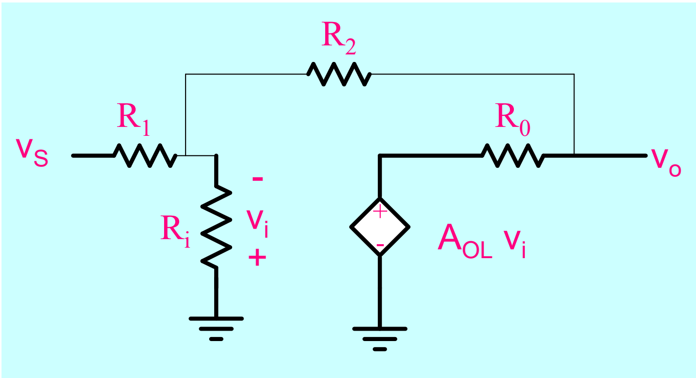
Open loop

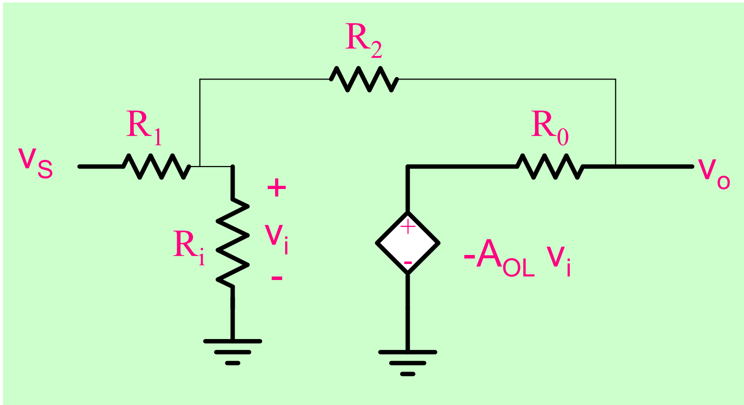
Most Opamp Circuits employ negative feedback

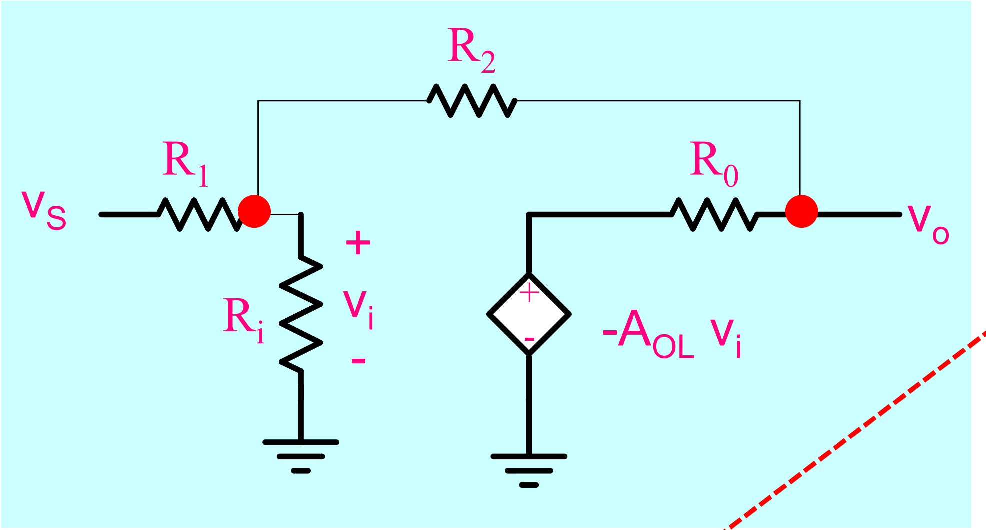
Inverting amplifier











Nodal Analysis

$$\frac{v_S - v_i}{R_1} = \frac{v_i}{R_i} + \frac{v_i - v_o}{R_2} \quad (1)$$

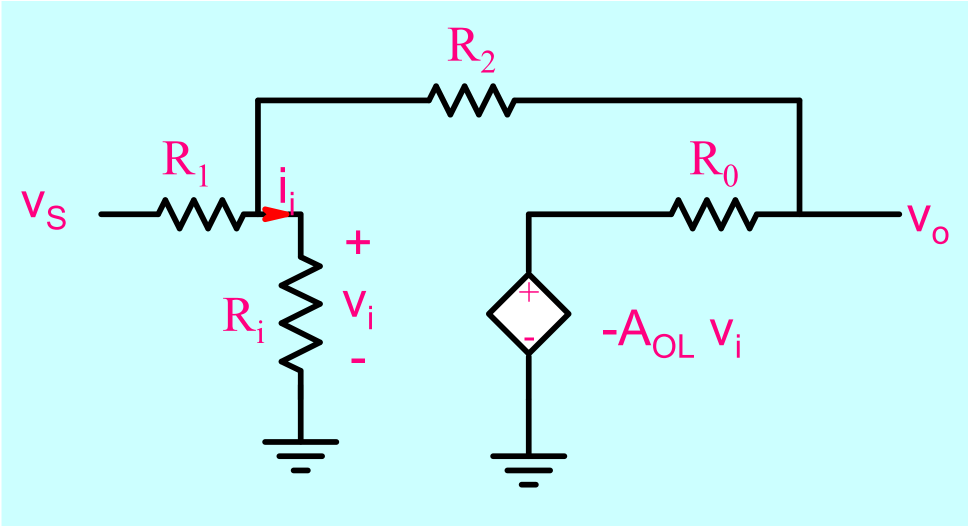
$$\frac{-A_{OL} v_i - v_o}{R_o} = \frac{v_o - v_i}{R_2} \quad (2)$$

$$\frac{v_S}{R_1} = -\frac{v_o}{R_2} + v_i \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_i}\right) \quad (3)$$

$$v_i = v_o \frac{\frac{1}{R_o} + \frac{1}{R_2}}{\frac{-A_{OL}}{R_o} + \frac{1}{R_2}} \quad (4)$$

As $A_{OL} \to \infty \quad v_i \to 0$

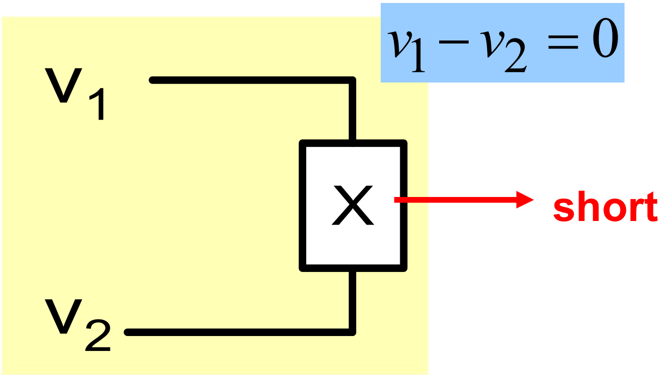
This is called the Virtual Ground property

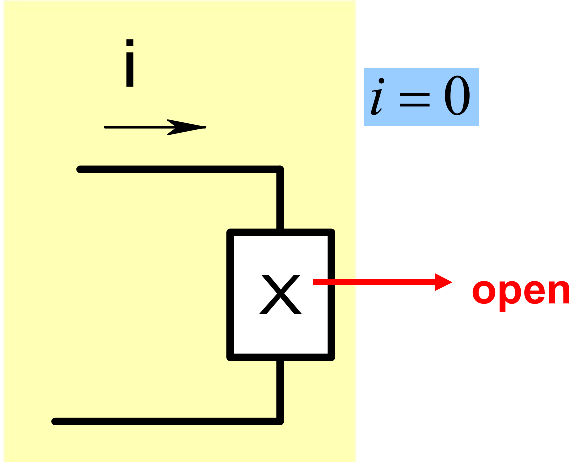


$$\text{As } A_{OL} \rightarrow \infty \quad v_i \rightarrow 0$$

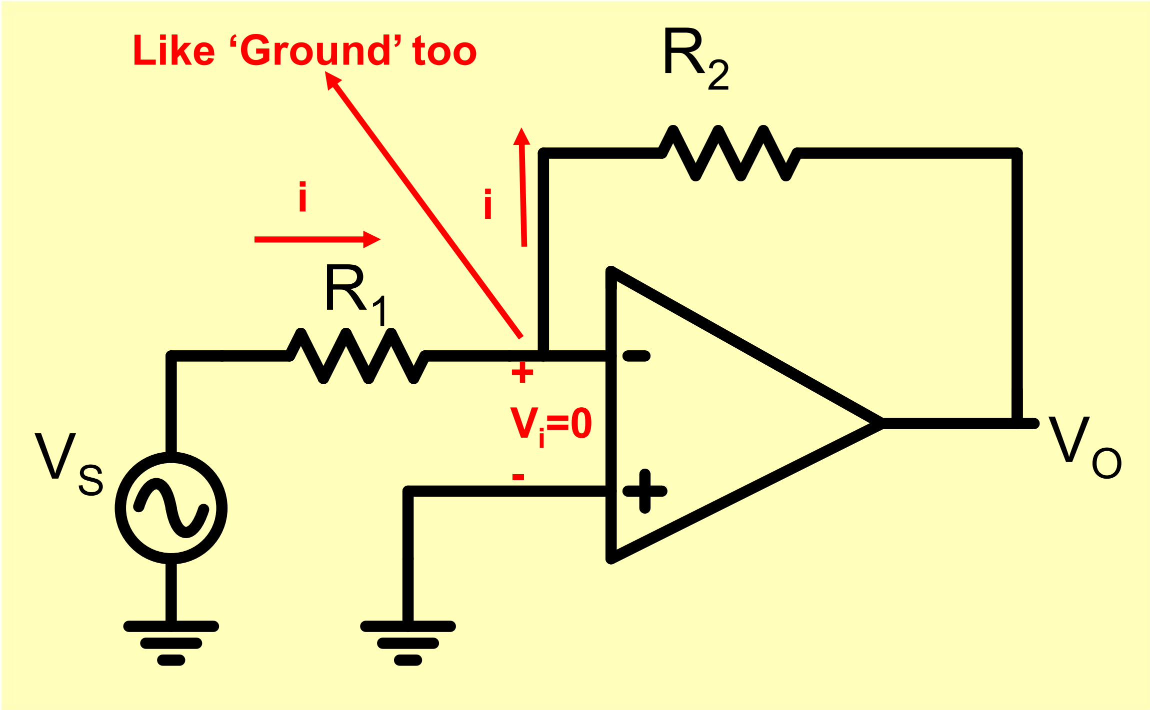
This implies that : $i_i \rightarrow 0$

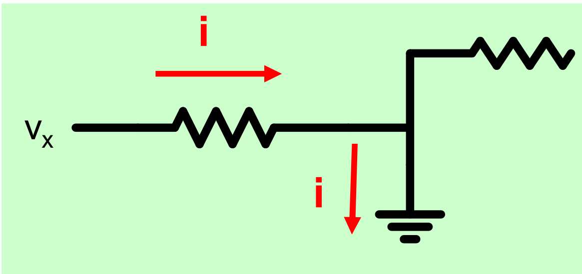
No current flows in or out of either inverting or non-inverting terminals of an ideal opamp





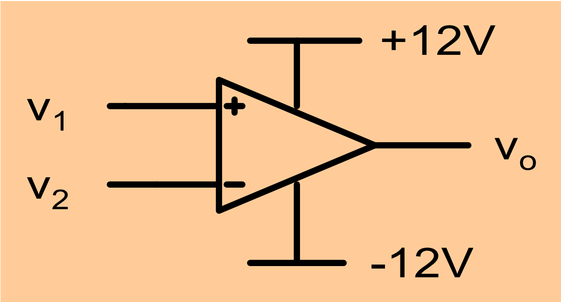
Can something be both a short as well as open circuit ?





Hence the name Virtual ground

Virtual Ground Property



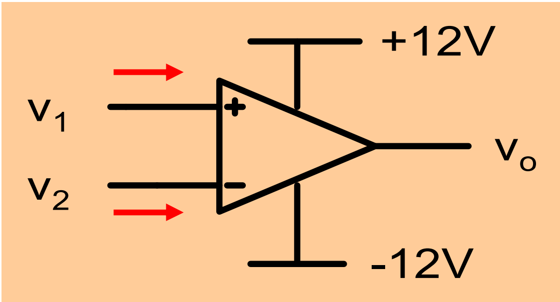
$$v_1 \cong v_2$$

In an opamp with negative feedback, the voltage of the inverting terminal is equal to the voltage of the non-inverting terminal if the gain of the opamp is sufficiently high

This property does not hold under certain conditions such as

- open loop,
- positive feedback
- or if the opamp is saturated.

Two important property for analyzing ideal opamp circuits under negative feedback



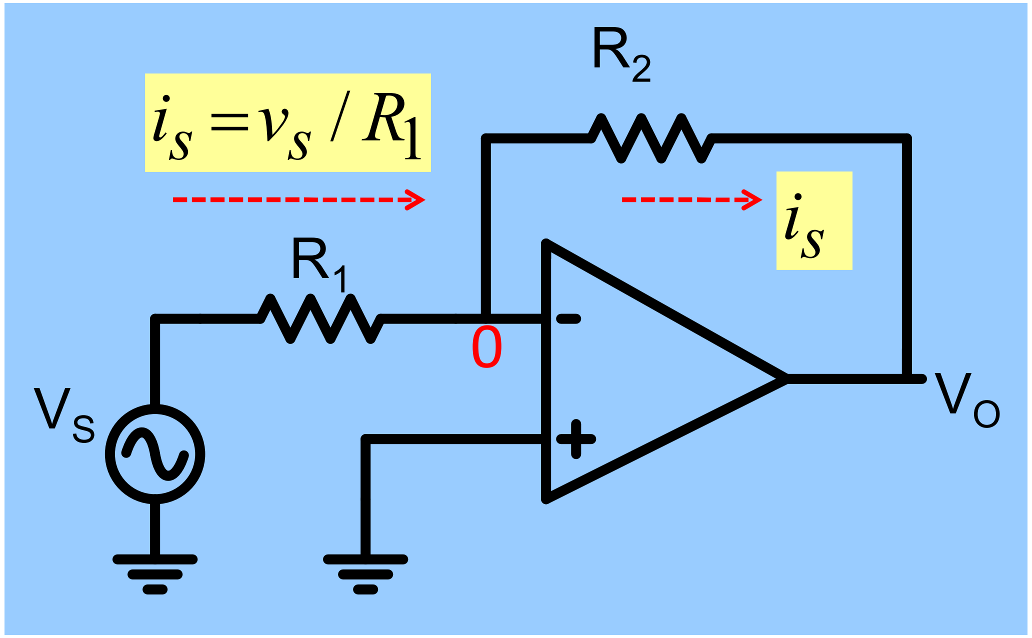
$$1. \quad v_1 = v_2$$

$$2. \quad i_1 = i_2 = 0$$

At the input side opamp appears to be like a short and an open circuit simultaneously !

Inverting amplifier

Re-analyze inverting amplifier with these properties



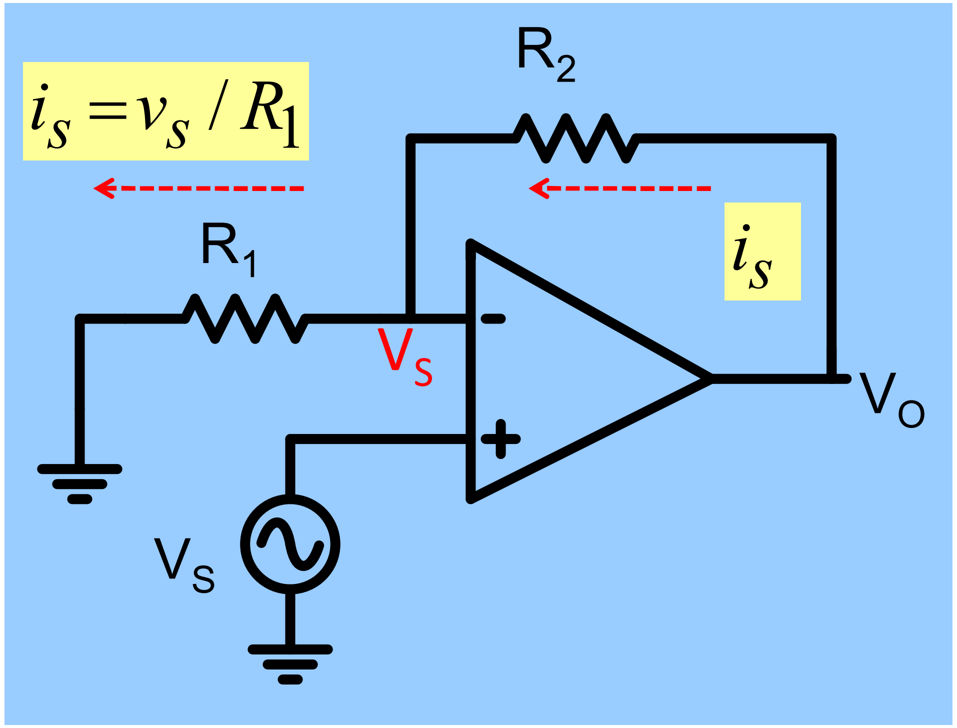
$$\frac{0 - v_o}{R_2} = i_s = \frac{v_s}{R_1}$$

$$\frac{v_o}{v_S} = -\frac{R_2}{R_1}$$

Non-Inverting Amplifier

$$1. \quad v_1 = v_2$$

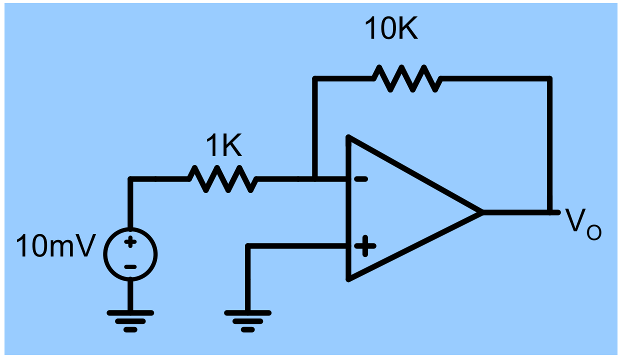
$$2. \quad i_1 = i_2 = 0$$



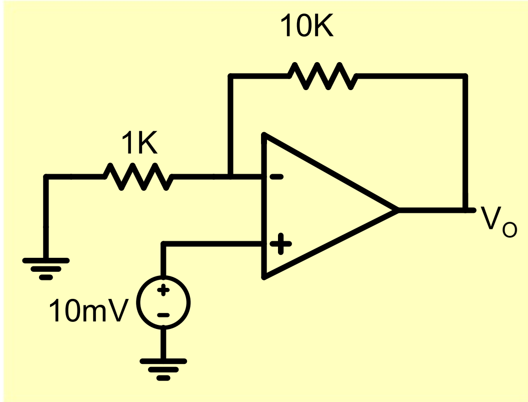
$$\frac{v_o - v_S}{R_2} = i_s = \frac{v_s}{R_1}$$

$$\frac{v_o}{v_S} = 1 + \frac{R_2}{R_1}$$

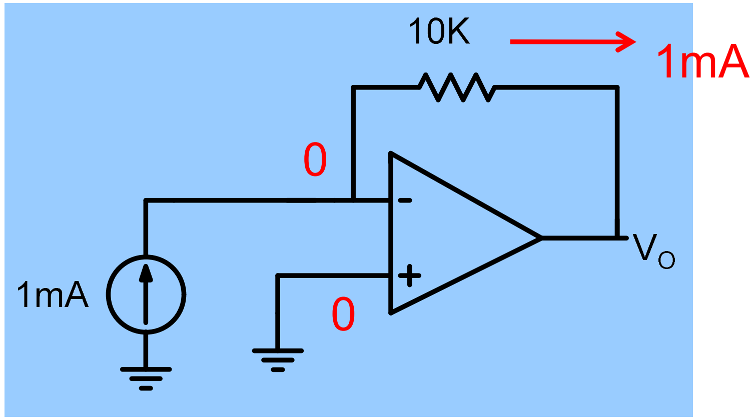
Examples



$$\frac{v_o}{v_S} = -\frac{R_2}{R_1} \Rightarrow v_o = -100mV$$



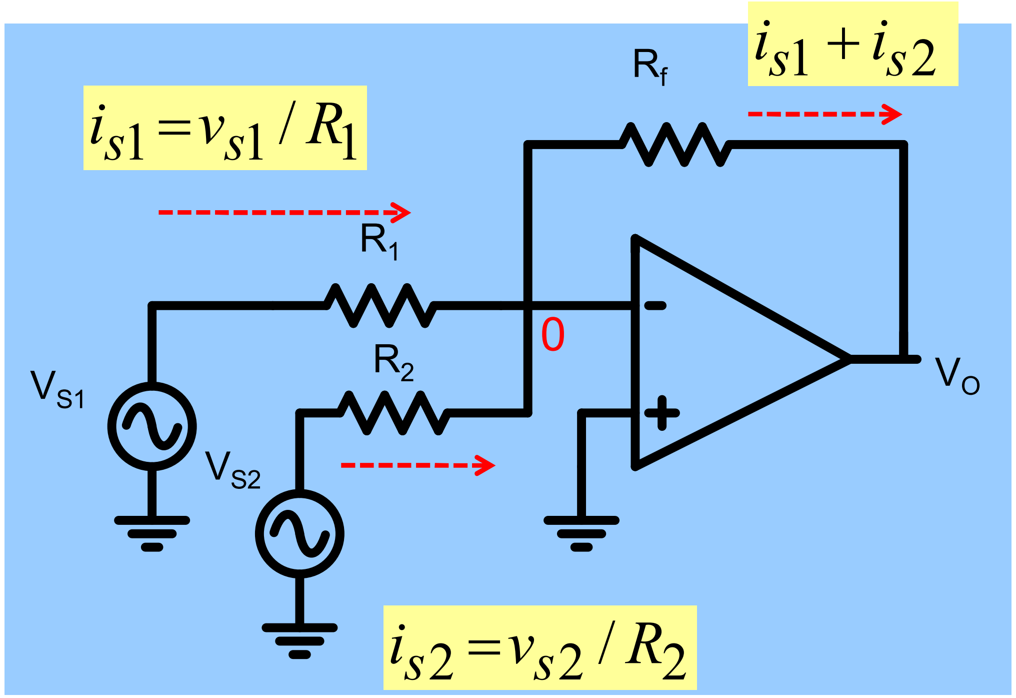
$$\frac{v_o}{v_S} = 1 + \frac{R_2}{R_1} \Rightarrow v_o = 110mV$$



$$\frac{0 - v_o}{10K} = 1mA$$

$$v_o = -10V$$

Adder

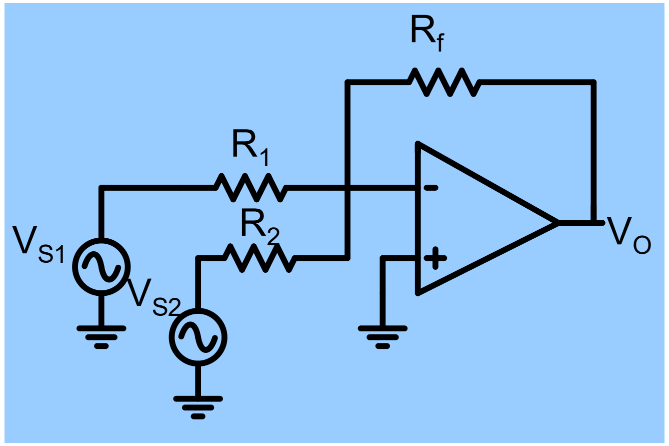


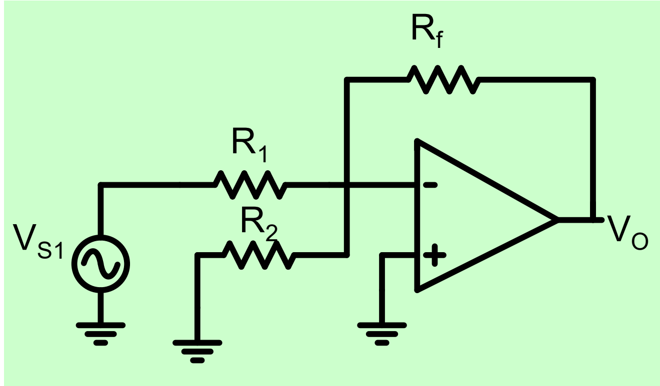
$$\frac{0 - v_o}{R_f} = i_{s1} + i_{s2} = \frac{v_{s1}}{R_1} + \frac{v_{s2}}{R_2}$$

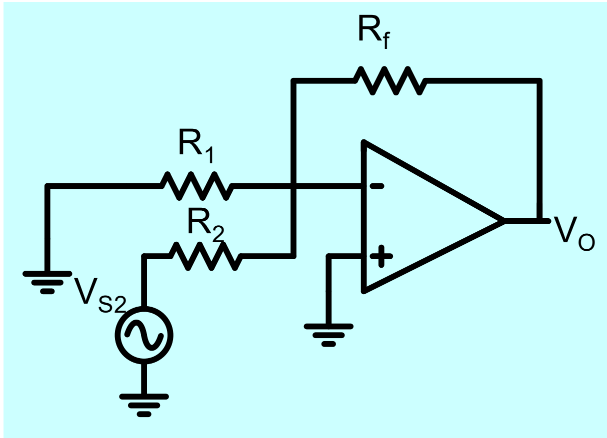
$$v_o = -\left(\frac{R_f}{R_1} v_{s1} + \frac{R_f}{R_2} v_{s2}\right)$$

$$\text{For } R_1 = R_2 = R \quad v_o = -\frac{R_f}{R}(v_{s1} + v_{s2})$$

Alternative Analysis





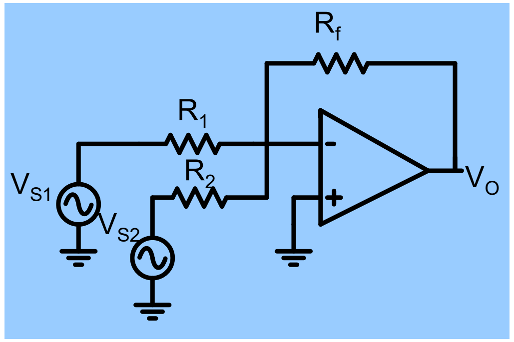


$$v_o = -(\frac{R_f}{R_1})v_{s1} \quad + -(\frac{R_f}{R_2})v_{s2}$$

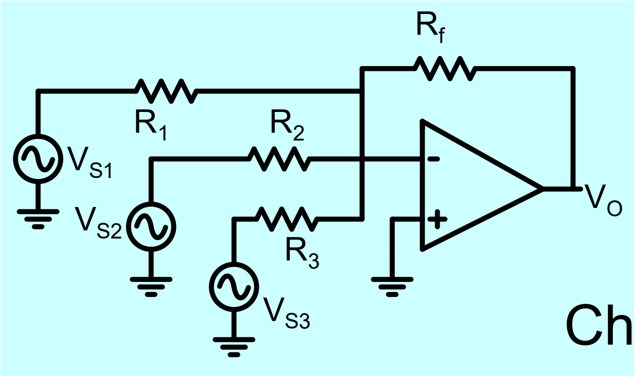
Design Example

Design a circuit that would generate the following output given three input voltages vs1, vs2 and vs3.

$$v_o = -10v_{s1} - 4v_{s2} - 5v_{s3}$$



$$v_o = -\frac{R_f}{R_1}v_{s1} - \frac{R_f}{R_2}v_{s2}$$

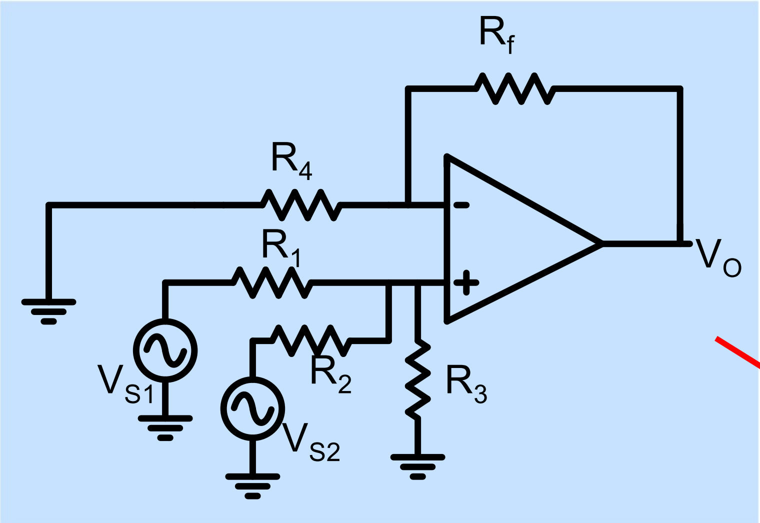


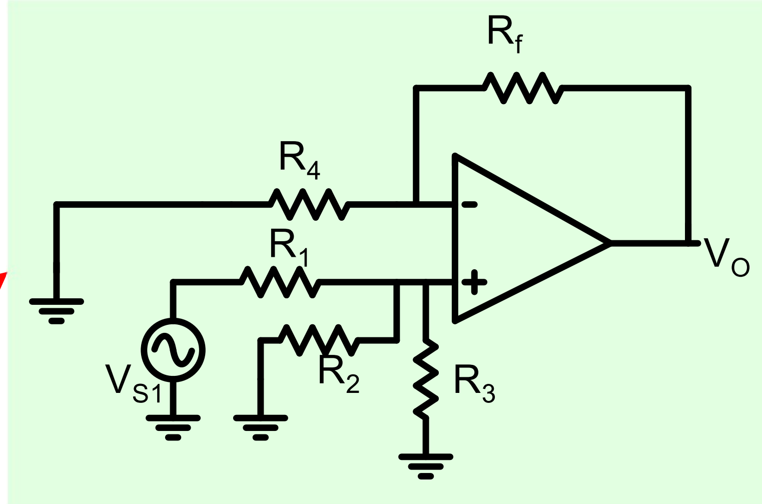
$$v_o = -\frac{R_f}{R_1}v_{s1} - \frac{R_f}{R_2}v_{s2} - \frac{R_f}{R_3}v_{s3}$$

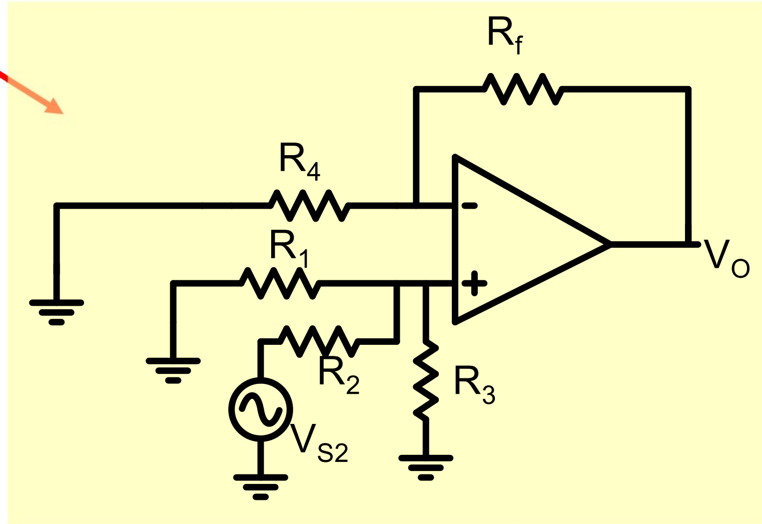
Choose : $R_f = 10K$ $\Rightarrow R_1 = 1K$

$\Rightarrow R_2 = 2.5K$ $\Rightarrow R_3 = 2K$

Adder



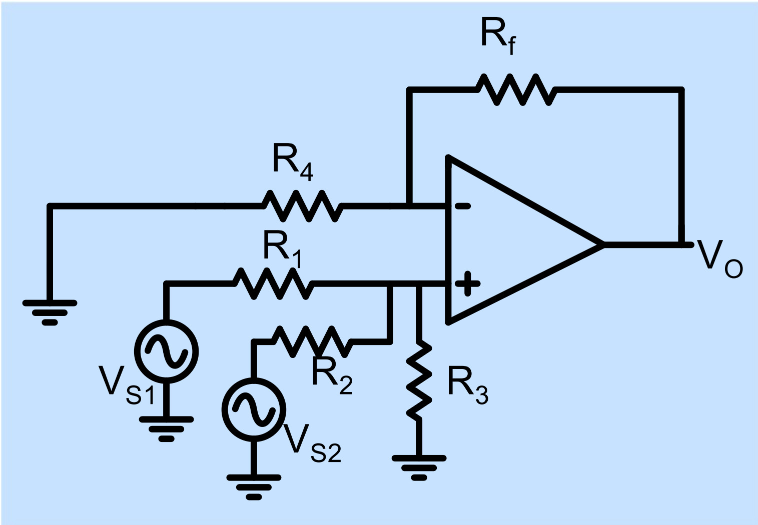




$$v_o = v_{s1} \frac{R_2 \| R_3}{R_2 \| R_3 + R_1} \times \left(1 + \frac{R_f}{R_4}\right)$$

$$+ v_{s2} \frac{R_1 \| R_3}{R_1 \| R_3 + R_2} \times \left(1 + \frac{R_f}{R_4}\right)$$

Adder



$$v_o = v_{s1}\frac{R_2 \| R_3}{R_2 \| R_3 + R_1} \times \left(1 + \frac{R_f}{R_4}\right)$$

$$+ v_{s2}\frac{R_1 \| R_3}{R_1 \| R_3 + R_2} \times \left(1 + \frac{R_f}{R_4}\right)$$

High entropy expression !

$$R_P = R_1 \| R_2 \| R_3$$

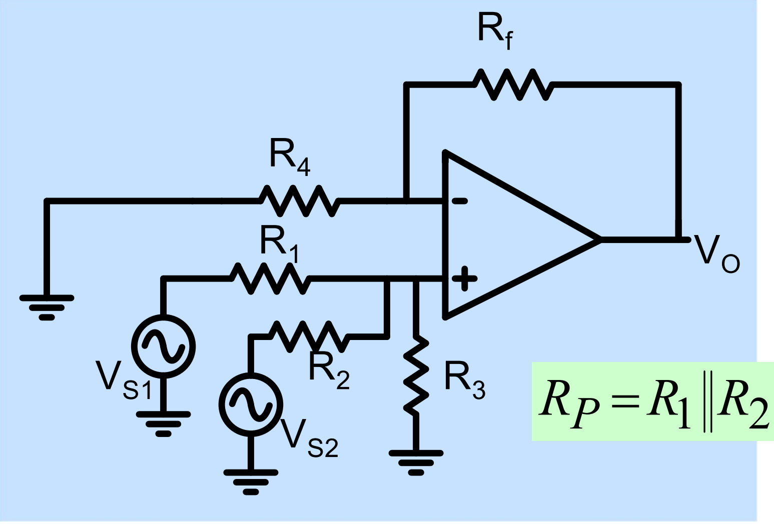
$$v_o = \left(\frac{R_p}{R_1} v_{s1} + \frac{R_p}{R_2} v_{s2}\right) \times \left(1 + \frac{R_f}{R_4}\right)$$

Low entropy expression !

Design Example

Design a circuit that would generate the following output given three input voltages vs1, vs2 and vs3.

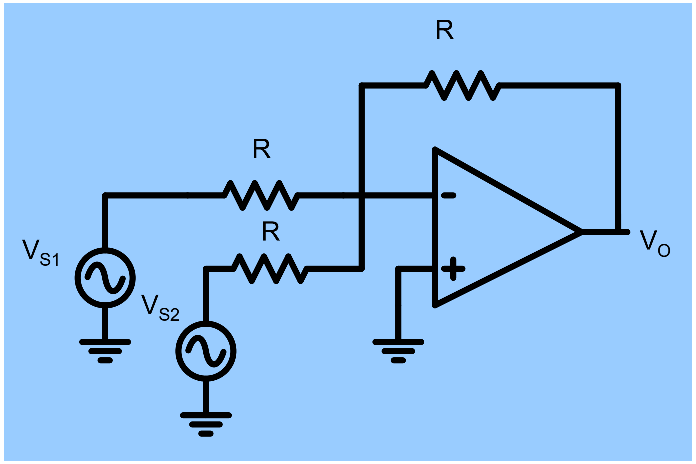
$$v_o = 10v_{s1} + 4v_{s2}$$



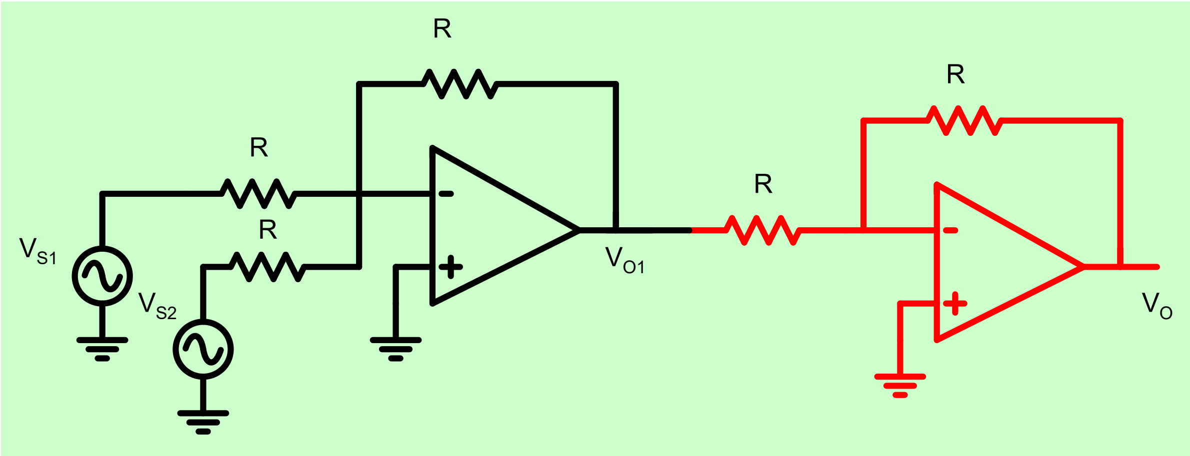
$$R_P = R_1 \| R_2 \| R_3$$

$$v_o = \left(\frac{R_p}{R_1}v_{s1} + \frac{R_p}{R_2}v_{s2}\right) \times \left(1 + \frac{R_f}{R_4}\right)$$

Homework problem !



$$v_o = -(v_{s1} + v_{s2})$$



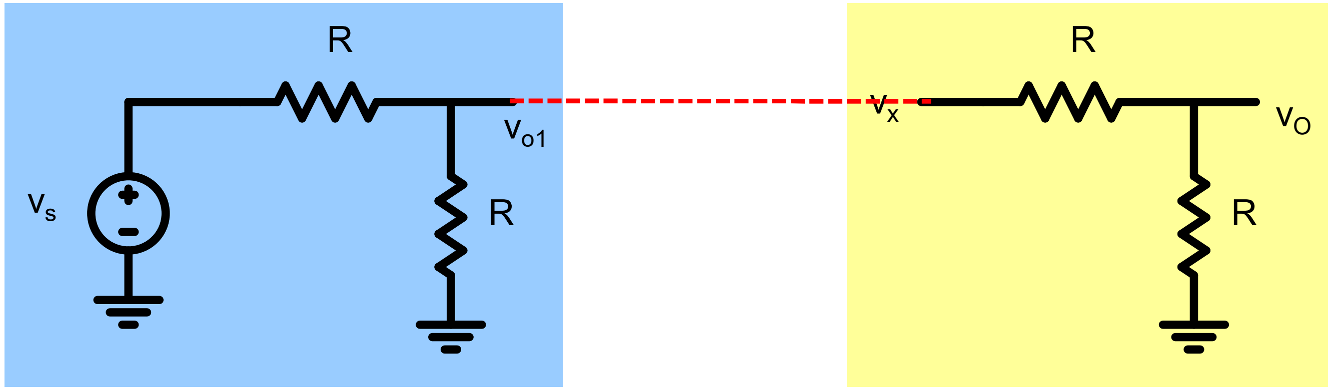
$$v_{o1} = -(v_{s1} + v_{s2})$$

$$v_o = -v_{o1}$$

$$v_o = (v_{s1} + v_{s2})$$

Have we made some assumption here ?

Example



$$\frac{v_{o1}}{v_s} = 0.5$$

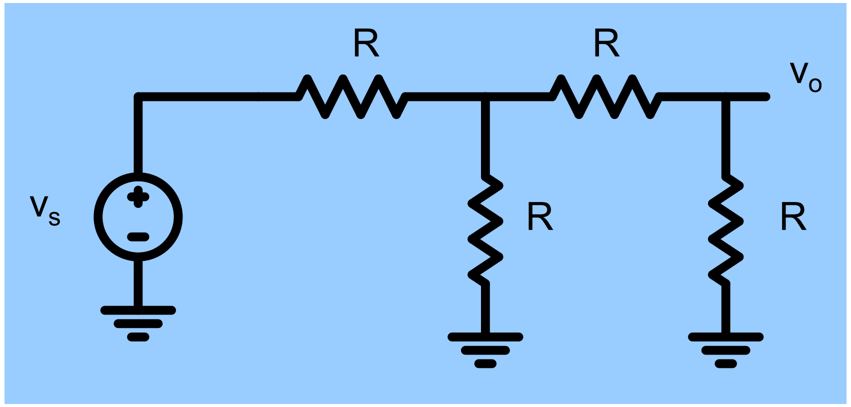
$$\frac{v_o}{v_x} = 0.5$$

$$v_{o1} = v_x$$

$$\frac{v_o}{v_x} = \frac{v_o}{v_{o1}} = 0.5$$

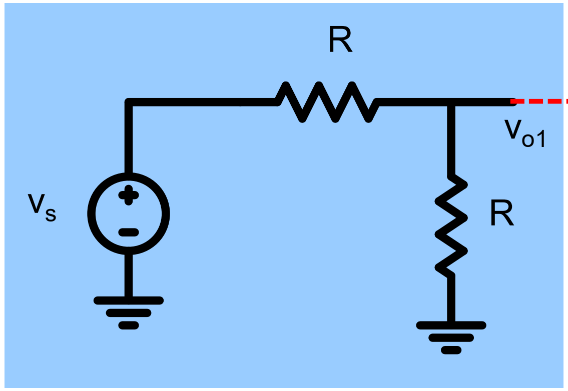
$$\frac{v_o}{v_s} = \frac{v_o}{v_{o1}} \times \frac{v_{o1}}{v_s} = 0.5 \times 0.5 = 0.25$$

BUT

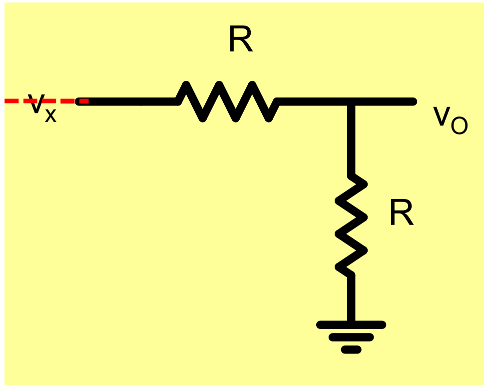


$$\frac{v_o}{v_s} = 0.2$$

Where is the error ?



$$v_{o1} = v_x$$



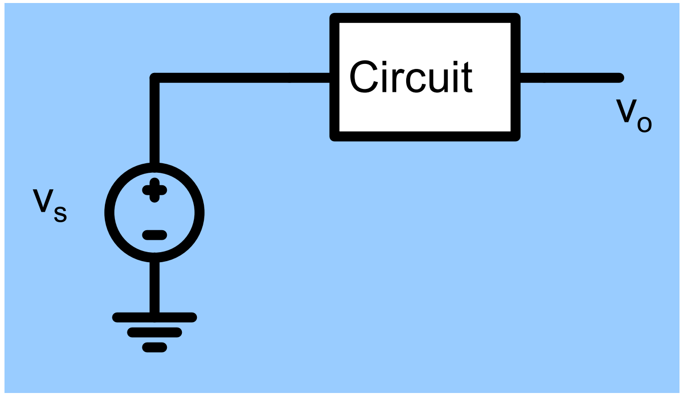
$$\frac{v_{o1}}{v_s} = 0.5$$

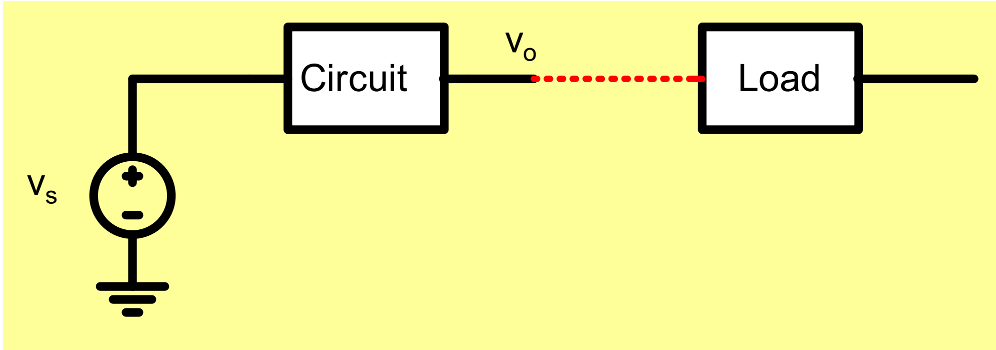
$$\frac{v_{o1}}{v_s} \neq 0.5$$

$$\frac{v_o}{v_x} = 0.5$$

Circuit-1 gets ‘loaded’ by circuit-2 and its output vs. input characteristics get modified.

Loading Effect

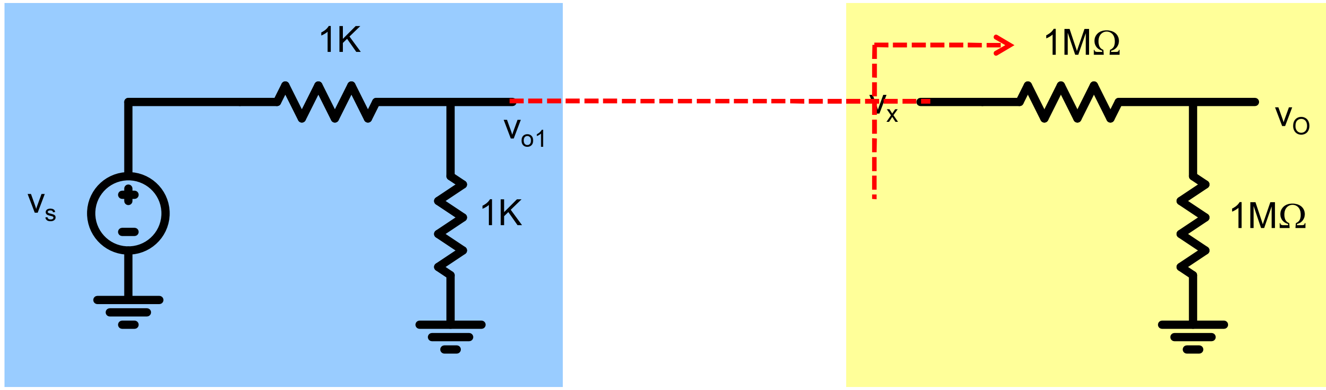




V_o in general gets altered when we connect a load to it

Under what conditions is change in V_O small upon connection of a load ?

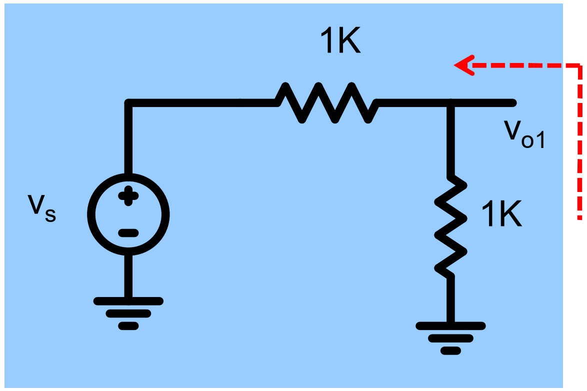
Example



$$\frac{v_{o1}}{v_s} = 0.5$$

$$\frac{v_{o1}}{v_s} \cong 0.5$$

We can describe this effect in terms of output resistance



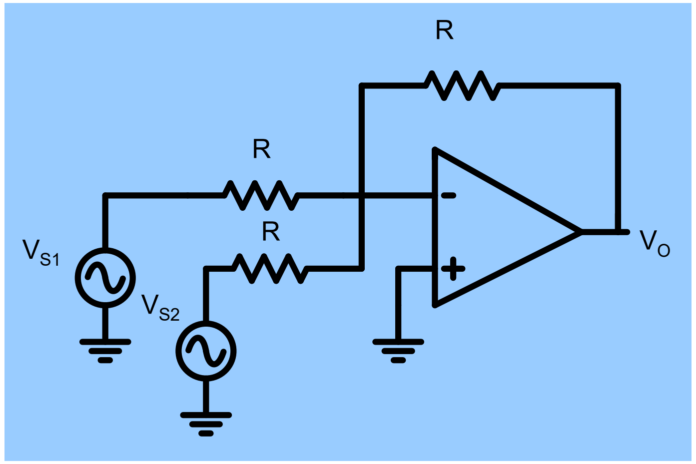
$$R_o = 0.5K$$

$$R_L = 2M\Omega$$

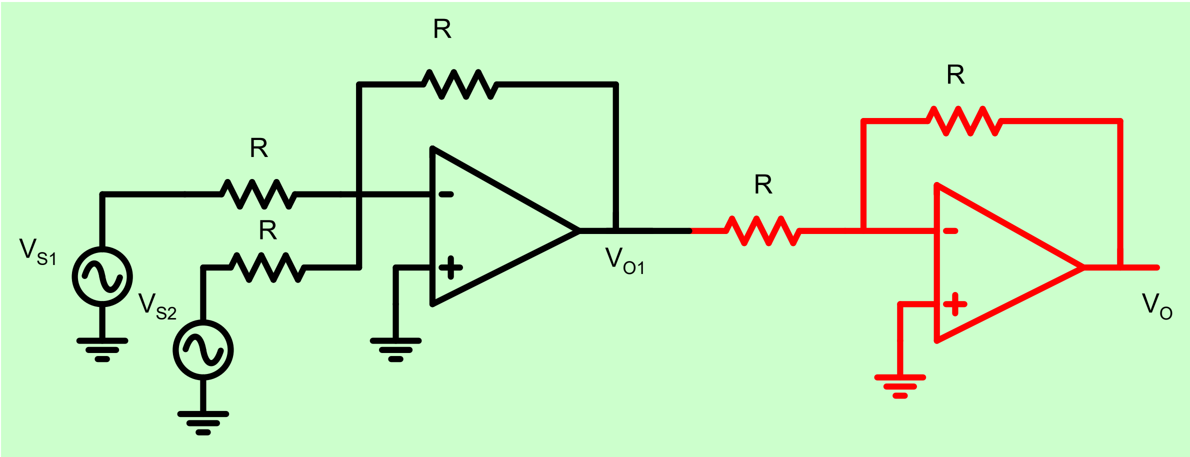
Loading Effect

Whenever output resistance of a circuit is much smaller than the load resistance, the loading effect is minimal.

$$R_o << R_L$$



$$v_o = -(v_{s1} + v_{s2})$$



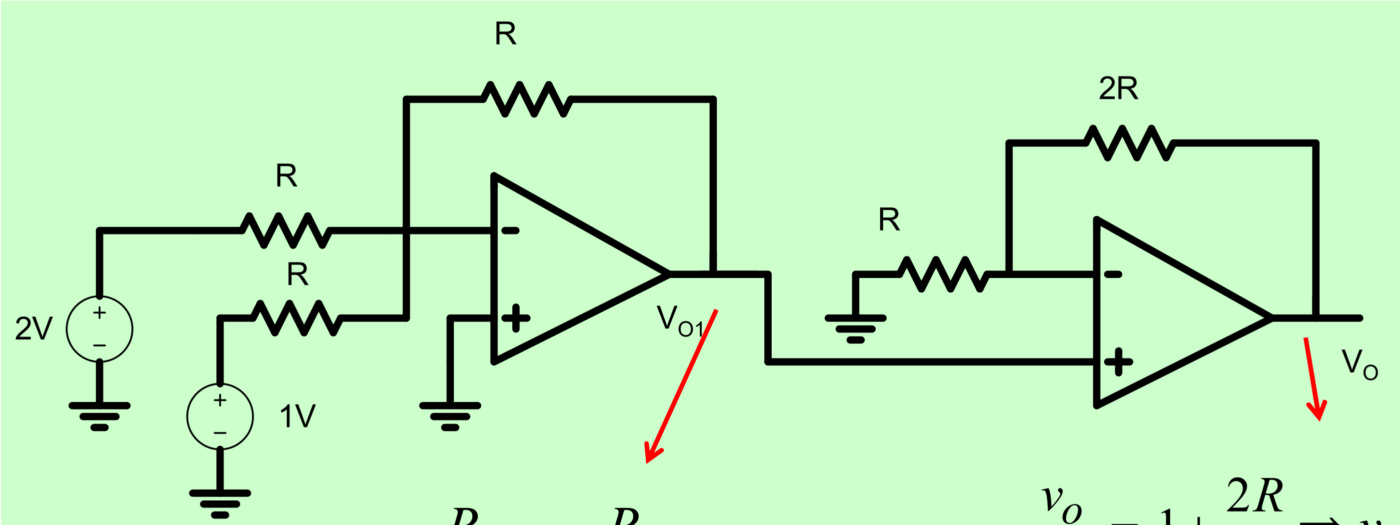
$$v_{o1} = -(v_{s1} + v_{s2})$$

$$v_o = -v_{o1}$$

$$v_o = (v_{s1} + v_{s2})$$

The assumption made here is that there is no loading which is reasonable because opamps have very low resistance

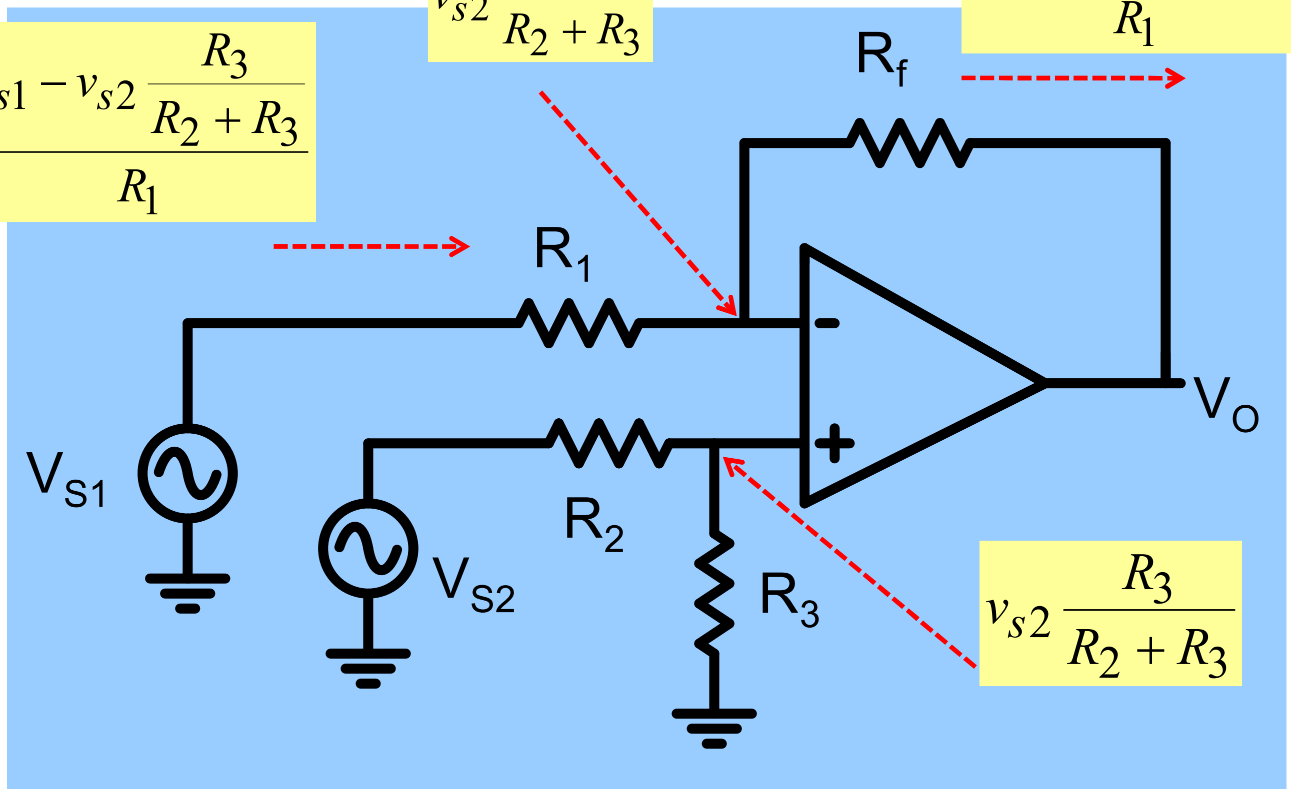
Example



$$v_{o1} = -\{\frac{R}{R}\times 1 + \frac{R}{R}\times 2\} = -3V$$

$$\frac{v_o}{v_{o1}} = 1 + \frac{2R}{R} \Rightarrow v_o = -9V$$

Subtractor



$$\frac{v_{s1} - v_{s2}\dfrac{R_3}{R_2 + R_3}}{R_1}$$

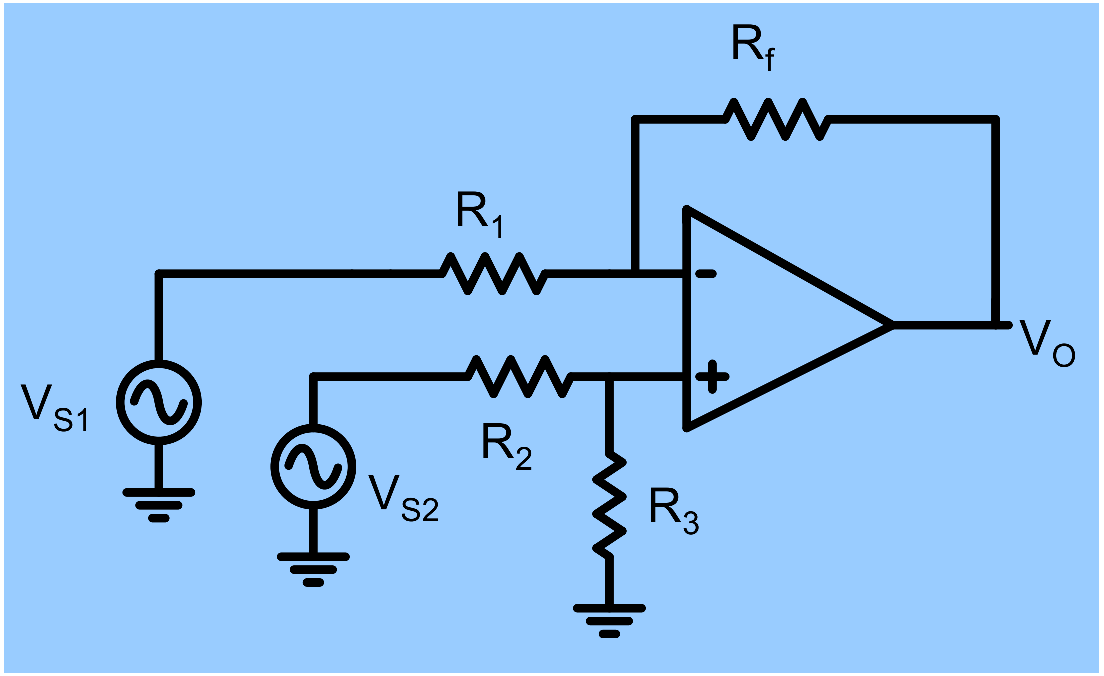
$$v_{s2}\frac{R_3}{R_2 + R_3}$$

$$\frac{v_{s1} - v_{s2}\dfrac{R_3}{R_2 + R_3}}{R_1}$$

$$v_{s2}\frac{R_3}{R_2 + R_3}$$

$$\frac{v_{s2}\dfrac{R_3}{R_2 + R_3} - v_o}{R_f} = \frac{v_{s1} - v_{s2}\dfrac{R_3}{R_2 + R_3}}{R_1}$$

$$v_o = v_{s2}\frac{\dfrac{R_3}{R_2}}{(1 + \dfrac{R_3}{R_2})}(1 + \frac{R_f}{R_1}) - (\frac{R_f}{R_1})v_{s1}$$

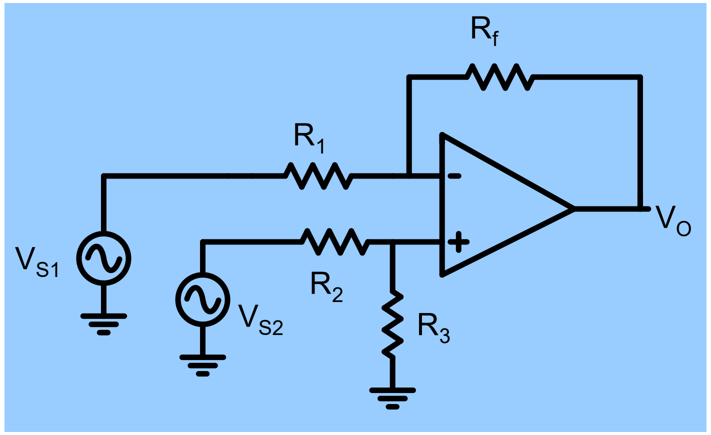


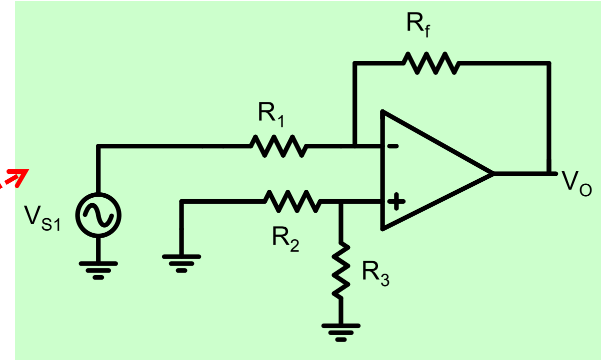
$$v_o = v_{s2}\frac{\frac{R_3}{R_2}}{(1+\frac{R_3}{R_2})}(1+\frac{R_f}{R_1}) - (\frac{R_f}{R_1})v_{s1}$$

Choose $\frac{R_3}{R_2} = \frac{R_f}{R_1}$

$$v_o = \frac{R_f}{R_1}(v_{s2} - v_{s1})$$

Subtractor: Alternative Analysis

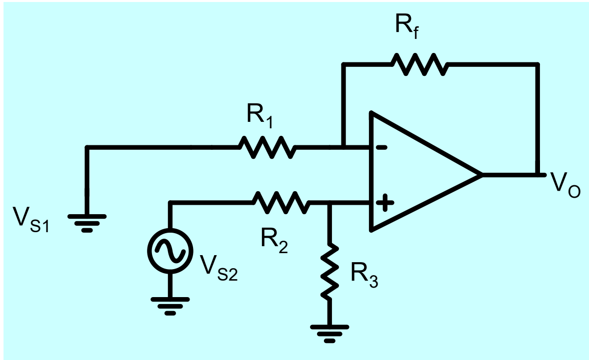




Inverting amplifier

Use superposition theorem

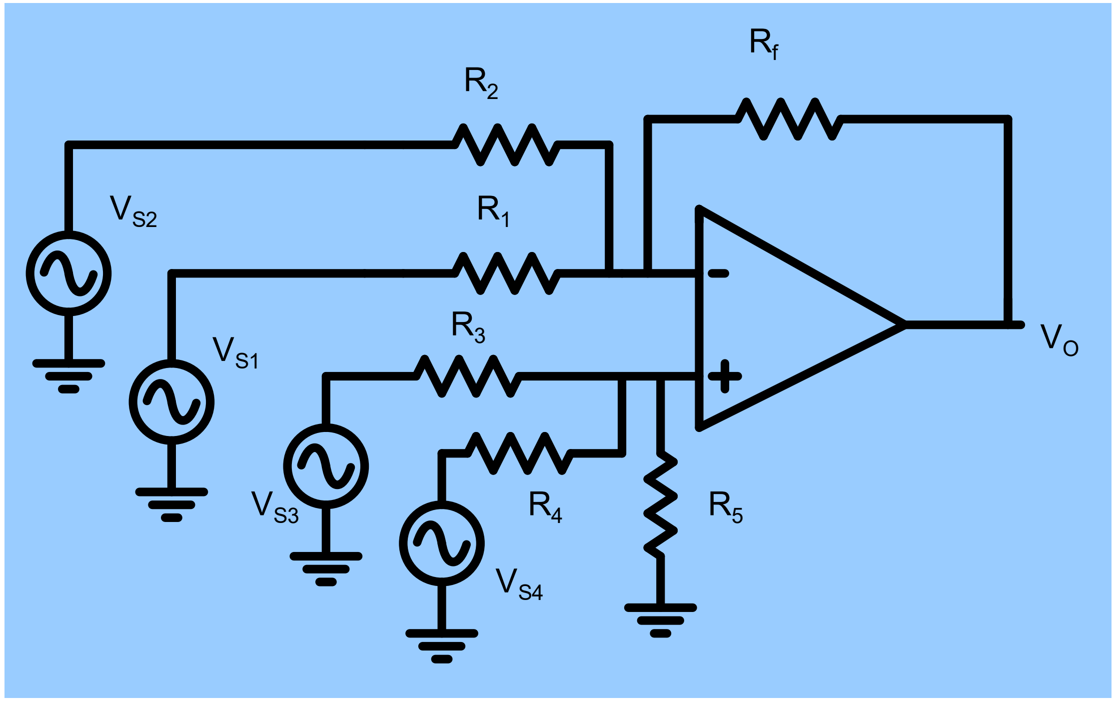
$$v_o = -(\frac{R_f}{R_1})v_{s1} \quad + \quad v_{s2}\frac{R_3}{(R_3+R_2)} \times (1+\frac{R_f}{R_1})$$



Non-inverting amplifier

Analysis is made simpler by **Re-Using** results derived earlier

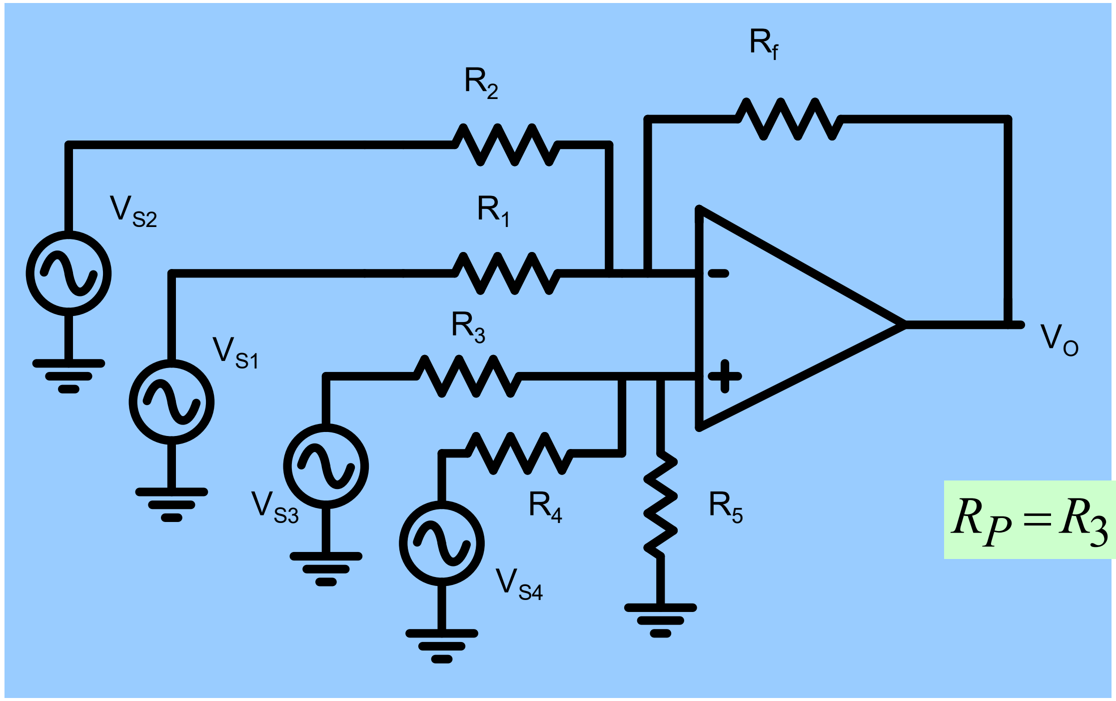
Adder/Subtractor



$$v_o = -\left(\frac{R_f}{R_1}\right)v_{s1} + -\left(\frac{R_f}{R_2}\right)v_{s2} + v_{s3}\frac{R_5\|R_4}{R_5\|R_4 + R_3} \times\left(1+\frac{R_f}{R_1\|R_2}\right)$$

$$+ v_{s4}\frac{R_5\|R_3}{R_5\|R_3 + R_4} \times\left(1+\frac{R_f}{R_1\|R_2}\right)$$

Adder/Subtractor

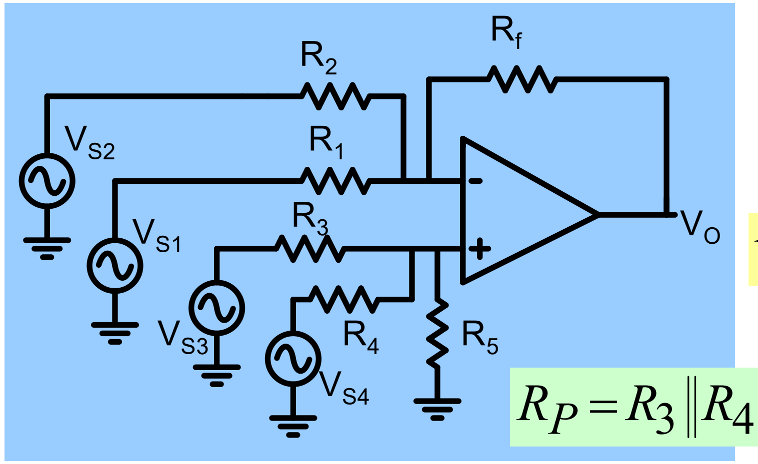


$$R_P = R_3 \| R_4 \| R_5$$

$$v_o = -\left(\frac{R_f}{R_1}\right)v_{s1} + -\left(\frac{R_f}{R_2}\right)v_{s2} + v_{s3}\frac{R_P}{R_3} \times \left(1 + \frac{R_f}{R_1 \| R_2}\right)$$

$$+ \quad v_{s4}\frac{R_P}{R_4} \times \left(1 + \frac{R_f}{R_1 \| R_2}\right)$$

Example



$$v_o = -10v_{s1} - 4v_{s2} + 5v_{s3} + 2v_{s4}$$

$$R_P = R_3 \| R_4 \| R_5$$

$$v_o = -(\frac{R_f}{R_1})v_{s1} - -(\frac{R_f}{R_2})v_{s2} + (1 + \frac{R_f}{R_1 \| R_2}) \times \frac{R_P}{R_3} v_{s3} + (1 + \frac{R_f}{R_1 \| R_2}) \times \frac{R_P}{R_4} v_{s4}$$

Choose : $R_f = 10K$ $\Rightarrow R_1 = 1K$ $\Rightarrow R_2 = 2.5K$

$\Rightarrow \frac{R_P}{R_3} = 0.33$ $\Rightarrow \frac{R_P}{R_4} = 0.133$ $\Rightarrow \frac{R_4}{R_3} = 2.5$

Choose : $R_3 = 1K$ $\Rightarrow R_4 = 2.5K$ $\Rightarrow R_P = 0.33K$ $\Rightarrow R_5 = 0.625K$